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THESIS

NUCLEATE BOILING HEAT TRANSFER STUDY OF DIRECT IMMERSION COOLING OF A 3X3 ARRAY OF VERTICALLY ORIENTATED ELECTRONIC COMPONENTS IN A DIELECTRIC LIQUID

by

Frank A. Arata

September 1992

Thesis Advisor: M. D. Kelleher

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Nucleate Boiling Heat Transfer Study of Direct Immersion Cooling of A 3X3 Array of Vertically Orientated Electronic Components in A Dielectric Fluid

by

Frank A. Arata
Lieutenant, United States Navy
B.S., United States Naval Academy, 1986

Submitted in partial fulfillment
of the requirements for the degree of

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Author: [redacted]
Frank A. Arata

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M.D. Kelleher, Thesis Advisor

[redacted]
M.D. Kelleher, Chairman
Department of Mechanical Engineering

ABSTRACT

Direct application of two-phase heat transfer in the liquid cooling of electronic components in fluorinated hydrocarbons (FC-72), is severely inhibited by the excessive amount of superheat required to initiate nucleate boiling. This phenomenon is well documented. To experimentally study the effects of nucleate pool boiling, a test chamber was constructed. This chamber utilized a substrate with nine chips on it and a platinum wire of 0.05 mm diameter. The wire was progressively heated to produce a plume of increasing intensity. A study was made of the effects of the boiling wake from the wire on the heat transfer from the chips.

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I. INTRODUCTION

A. BACKGROUND

As the trend in electronic components continues toward miniaturization with greater and greater power requirements, the heat flux required to cool these chips greatly increases. In general, there are several alternative methods available to cool electronic components. Air cooling is one method. Some of the techniques available to augment air cooling include using enhanced surfaces, increasing the air velocity, and using a turbulator to trip the air flow. These methods are unable to provide the cooling necessary to support the packaging density required in some of today's electronic machines.

Another method available is conduction plates. Conduction plates are normally water cooled and are able to handle much greater heat fluxes than air cooled systems. The effectiveness of conduction plates can be enhanced through the use of finned surfaces, microchannels and increasing the fluid flow rate. While microchannels are very effective, they incur large pressure drops. The hardware which is required to accomplish either of these two methods is cumbersome in any application [Ref. 1]

Still another method is the use of direct liquid cooling technology. Liquid forced convection cooling is one promising method. This method requires utilizing inert dielectric fluorocarbons which are up to ten times more effective than air in cooling electronic components. Unlike liquid phase change methods, this method does not require a condenser, and offers direct temperature control by varying the inlet temperature. Liquid forced convection is effective and is used in the Cray-2 super computer. Through the use of enhanced surfaces an order of magnitude enhancement of heat transfer is possible over conventional surfaces. While this method is very impressive, to achieve even higher heat transfer rates, pool boiling, flow boiling or liquid film evaporation must be used [Ref. 1]

Oktay [Ref. 2] illustrates this problem. His example assumes that heat loss due to radiation is negligible as compared to heat loss by convection. The power dissipation of 10 W on a 5x5 mm chip yields a heat flux of 5x10^5 W/m^2, which is only 20 times less than that on the surface of the sun. At this large heat flux, the sun's surface temperature exceeds 6000 C, in comparison to the 100 C maximum temperature today's chips are designed to operate at. If the chip were cooled in still air, it's temperature would theoretically exceed 6000 C. With forced convection, the chip's temperature would exceed 1000 C when cooled with common gasses, and drop to about 50 C with common liquids. However, common liquids can not be used because they conduct electricity. If, on the other hand, the heat is conducted away by means of a copper stud pressed against the chip, the chip's temperature can be lowered to 30 C, assuming the copper stud is held at 25 C and the contact between the stud and the chip is PERFECT. If a small air gap of 1mm is introduced between the same chip and the stud, the chip's temperature will reach 600 C. Immersion cooling with phase change can lower the chip's temperature to approximately 45 C to 55 C if a fluorocarbon is used [Ref. 2]. These fluorocarbon's are ideally suited because they do not conduct electricity and are inert.

Cooling electronic components by pool boiling is being extensively researched. This research has focused on three primary areas: (1) reducing temperature excursion at incipient boiling, (2) reducing wall superheat during nucleate boiling and (3) enhancing critical heat flux [Ref. 3].

B. PREVIOUS WORK

The present work is a follow on to the study conducted by LT Robert Egger at the Naval Postgraduate School [REF 4]. The apparatus utilized was similar to Egger's, yet there were some major differences. Egger's apparatus contained only one board with five platinum wires on it, while this study's apparatus contains only one platinum wire and an electronic component with a 3X3 arary of chips. Egger studied the effect a plume from the lowest wire had on the top four wires heat transfer behavior, while this study investigates the effect the plume from the platinum wire had on the electronic component. Egger reached the following conclusions:

1. A constant source of bubble generation from below is an effective way to eliminate the boiling curve overshoot and hysteresis loop associated with low surface tension fluids.

2. At low heat fluxes, proximity to the lower wire is important for heat transfer enhancement to occur. This dependency reduces as the heat flux increases on the upper wires.

3. The buoyant plume created by the bottom wire improved convective heat transfer on the wire directly above it but had negligible impact on the upper wires.

4. The sudden drop of the wall temperature after the onset of boiling was seen to be the results of the following:

> Bubbles from the lower wire activating the inactive nucleation sites on the upper wires resulting in boiling heat transfer from the upper wires.
>
> An additional force convection enhancement due to the nucleation bubbles from wire 1 breaking up the thermal boundary layer about the upper wires is believed to exist.

Danielson et al, [Ref. 5] studied the saturated pool boiling characteristics of commercially available perflourinated liquids. This study utilized a modified, 1 liter glass flask suspended inside an outer flask, and a 0.25 mm platinum wire. Their study made the following conclusions:

1. Nucleate boiling characteristics of highly wetting liquids can be predicted with correlations developed for water and other fluids having widely different properties, and are highly dependent on the heating surface. Values for the constants in Rohsenow-type correlations are given in the paper.

2. Saturated pool boiling curves for inert liquids differing widely in boiling point are almost identical with one another on a particular heater. Similarities include the nucleate boiling curve and critical heat flux as well as single phase convective curve.

3. Single phase convection data are predicted accurately by a correlation developed by Kuehn and Goldstein.

4. Superheat excursions at boiling incipience appear to always occur, but their extent can vary widely.

5. The apparent radii of embryo nucleation bubbles were

calculated as 0.1 to 0.2 micro meters.

6. Cooling efficiency with these fluids in the nucleate boiling zone is good, corresponding to an overall thermal resistance of 1.2 to 2.1 deg C/W for a 1 cm^2 surface.

7. Departure from nucleate boiling occurs at heatfluxes between 16 and 23 W/cm^2 for fluids boiling at 100 deg C and below. Corresponding temperature differences are 21 to 29 K. Average heat flux for each fluid agree within 19% of calculated values, but scatter is quite wide.

8. The dependence of heat flux on surface characteristics may require further study.

Marto and Lepere [Ref. 6] conducted research on the effects of enhanced surfaces on pool boiling. They used a plain cooper tube, a Hitachi Themoexcel-E Surface and a Wieland Gewa-T surface. They utilized two dielectric fluids, FC-72 and R-113 during their experiment. They observed the following:

1. For R-113, the enhanced surfaces show a two to tenfold increase in the heat-transfer coefficients when compared to the plain tube, whereas for FC-72 the enhanced surfaces only show a two to five fold increase.

2. The degree of superheat required to activate the enhanced surfaces is less than the plain tube, and is sensitive to initial surface conditions and fluid properties. The superheat required for R-113 is approximately twice as large as those required for FC-72, which is in agreement with existing theory. Consequently, the temperature overshoot problem and the resulting nucleate boiling hysteresis pattern is less severe with this liquid than with R-113.

3. In using these enhanced surfaces to cool electronic equipment, care must be exercised at low heat fluxes where temperature overshoots could lead to uncertain semiconductor junction temperatures and lower reliability.

You, et al, [Ref. 7] conducted an investigation of nucleate boiling incipience with a highly wetting dielectric fluid (R-113). They used both a chromel wire and a platinum heater. Here is a summary of their findings:

1. The incipience superheat excursion, under the conditions of their study was highly non-repeatable. The data was best represented using statistical form.

2. Superheat levels of 24.0 to 38.9 degree Celsius at

incipience were measured for drawn chromel wires. Corresponding bubble radii of 0.10 to 0.23 micrometers were computed. The platinum heater data showed incipience super heats of 49.1 to 72.5 degrees Celsius. Embryonic bubble radii of 0.023 to 0.062 micro meters were computed for the data. The higher superheat values measured on the platinum heater are presumed to result from the absence of large cavities capable of entrapping bubble nuclei for incipience.

3. Superheat excursions at the onset of nucleate boiling were strongly dependent upon the values of wall superheat at the beginning of heat-up phase of the cycle (and at the end of the cool down phase of the previous cycle). This behavior is believed to be peculiar to low-wetting-angle fluids where the minimum radius of the incipience bubble embryo, within the cavity, establishes the wall superheat or flux required for incipience. Thus, the minimum superheat between cycles establishes the superheat required for incipience.

4. The tests with large steps in heat flux showed increases in superheat excursion values (at the same probability) of as much as 20% over those of the small, incremental heat flux tests. The probability curves for boiling incipience are, apparently, dependent on how the

heater is powered.

Bar-Cohen [Ref. 8] provides an overview of the hysteresis phenomena at the onset of nucleate boiling. In this overview he reviewed a wealth of literature on this subject and reached the following conclusions:

1. The vapor/gas volume trapped in microcavities along the surface by the liquid has been shown to establish the superheat required to initiate the boiling process.

2. The volume, as well as the vapor/gas surviving in a cavity after the cessation of boiling, is highly variable and leads to a wide distribution in the incipience superheat.

3. The understanding gained in developing a mechanistic model of boiling incipience makes it possible to predict the influence of fluid properties, surface properties, pressure, liquid velocity, and dissolved gas on the magnitude of the hysteresis and to interpret the experimentally observed effects of subcooling, enhanced surfaces, and liquid mixtures on this characteristic of boiling in highly-wetting liquids.

4. The examination of these parametric effects reveals that the superheat excursion is smaller for the

perfluorinated liquids than for the chloroflourocarbon, and can be further reduced, if not eliminated, by operation at increased system pressure, liquid velocity and dissolved gas content.

C. OBJECTIVE

The purpose of this work was to investigate the effects of the boiling wake from a heated platinum wire on the heat transfer from an electronic component with nine chips placed within the wake. The work was carried out in a chamber which was filled with a dielectric fluid, FC-72. The electronic component was immersed in the in the fluid and the effect of the boiling wake from the platinum wire on the heat transfer from the chips was studied.

II. EXPERIMENTAL APPARATUS

A. DESCRIPTION OF COMPONENTS

The chamber used in this study is a redesign of the earlier experimental chamber used in Egger's thesis [REF 4]. The chamber was redesigned to investigate boiling heat transfer from an actual 3X3 array of electronic chips instead from platinum wires as used by Egger.

Figure 1 is a schematic of the overall apparatus. The apparatus contains the test chamber, the four power supplies, the data acquisition unit and the computer. Figure 2 is a photograph of the actual experimental apparatus.

The center piece of the experimental chamber is the electronic component which is composed of a 3X3 array of electronic chips. The electronic component was mounted on an insert board and exposed to a plume from a platinum wire which was located below the chip. The electronic component was glued to the insert board by RTV sealant. The insert board has four holes in its corners, and it slides on four threaded rods. These four rods utilize spacers and a nut to control the boards horizontal distance from the platinum wire heater. The platinum wire heater is mounted on a 1.75 inch wide by 6.00 inch long plexiglass board and fits into a 0.25 inch thick grove in the wall of the test chamber. Four other boards also fit into this grove. By varying the order of these four boards and the heater, the vertical height between the electronic component and the platinum wire heater can be varied. The insert board and platinum wire are housed in the test chamber. The test chamber consists of a box constructed of 0.70 inch thick polycarbonate sheets with a 0.25 inch thick aluminum cover plate fitted with a rubber O-RING seal. The aluminum cover plate, which serves as the condenser, is mounted with three thermo-electric coolers. The vapor condenses on the surface and returns to the chamber via gravity. Three flat copper heaters are mounted on the base of the chamber. The heaters are used to raise the bulk fluid temperature to saturation and to degas the fluid. A total of twelve copper-constantan type thermocouples and five chip temperature sensors were used for temperature measurements.

1. ELECTRONIC COMPONENT

The electronic component used in the experiment consisted of nine Texas Instrument NWSC-EAL #00040TF chips mounted on a ceramic substrate. The electronic component was mounted on the insert board using a 732 RTV adhesive/sealant. The electronic component contains a 3X3 array of chips. The electronic component has eighteen leads connected to it. The electronic component was mounted inverted so that the leads from the chip would not effect the plume before it impinges on the chips. Figure 8 contains a picture of the electronic component mounted on the insert board. The chips are numbered sequentially from right to left, and bottom to top. Thus the top row's three chips are numbered 7,8,9 and the bottom rows chips are numbered 1,2,3. The chips in the left column, 9,6,3 and the chips in the right column 7,4,1 must be powered to the same level since they are connected in parallel. The chips in the center column can be powered individually, while the chips in the outside columns must be powered in parallel. The experiments were conducted with all of the chips powered in parallel. Chips 2,4,5,6 and 8 are equipped with temperature sensors. The temperature sensors are powered by a constant 1.0 milliamp current. The output voltage of the sensor is proportional to the chips temperature. The temperature of the chip was determined by utilizing the temperature versus voltage calibration curves calibrated prior to the start of the experiment. As the temperature of the chip increased the voltage of the chip decreased by approximately 1.9 millivolts per degree C.

The chip and its temperature sensor are encapsulated in a small box with a lid. The chip and its temperature sensors are mounted on the base of the box. The chip is then encapsulated by four walls and a thin brass lid. Between the chip and the lid a small air gap exists which increases the thermal resistance to heat transfer. Figure 9 contains a sketch of the chip, air gap and the lid.

2. Substrate Insert Board

The substrate is mounted on a 0.25 inch thick, 6.00 inch high, by 6.00 inch wide plexiglass board. Four small holes were drilled into the corners of the board's face so that the board could slide on the four threaded drill rods mounted on the rear face of the chamber. Spacers and four nuts control the boards horizontal location. The substrate is mounted in a 0.033 inch deep grove, which is a 2.00 inch square, one inch from the top of the board. The substrate is orientated so that the power and voltage terminals are located at the top of the board so as to not disturb the plume. The leads from this board are glued to the surface and connect to a power strip on the rear of the board. Figure 7 is a sketch of the insert board with the electronic component mounted on it. Figure 8 is a photo of the insert board with the lids on.

3. Platinum Wire Heater and Boards

One 4.0625 inch long platinum wire, 0.002 inch (0.05mm) in diameter, was mounted on a 6.433 inch long by 1.875 wide plexiglass strip. The wire was used to create the plume during the boiling experiment. The wire was mounted on two brass posts which protruded 0.375 inch normal to the face of the plexiglass strip. One post was fixed, while the other post was free to rotate. Two small plexiglass blocks were glued on the rear of the strip. After the platinum wire was connected to the two posts, set screws in the blocks were adjusted to tension the wire and prevent the free post from moving. By varying the order of the four boards and the heater the vertical distance between the electronic component and the platinum wire can be varied. Figure 11 contains a picture of the platinum wire heater and the four boards.

4. Test Chamber

The interior dimensions of the chamber are 6.00 inches long, by 2.375 inches wide, by 6.00 inches deep. The entire chamber was assembled using a bonding adhesive. A sketch of the chamber is shown in Figure 3. Figure 4 is photo of the chamber with the insert board and the platinum wire in place.

To permit access for instrumentation and power leads, a 0.75 inch diameter hole was placed in the lower corner of the rear face of the chamber. To ensure pressure equalization, a 0.25 inch hole was placed in the upper left corner of the front face. This hole is above the fluid level. Mounted securely in these holes were two eighteen inch lengths of tygon tubing. The open ends of the tube were suspended well above the test chamber.

On the interior side walls, slots are milled to permit the placement and removal of the platinum wire heater board and four spacers. Four threaded drill rods were mounted on the rear face of the chamber. The substrate insert board has four holes in it, and slides on these four rods. Spacers and four nuts control the boards horizontal location.

5. Aluminum Cover Plate

A 0.25 inch thick by 7.50 inch long by 4.00 inch wide aluminum cover plate was utilized as both a cover plate for the chamber and a condenser for the FC-72 vapor. Figure 5 is outside surface of the cover plate with the three electric coolers on the surface. Figure 6 is the inner surface of the condenser with the O-

Ring seal. Two thermocouples were mounted on the condenser surface. The thermocouples monitor the condenser's surface temperature. On the outside of the cover plate, three thermoelectric coolers were mounted to allow the cover plate to serve as a condenser for the vapor. To achieve a proper seal between the test chamber and cover plate, a rubber gasket was inserted between the chamber and the cover plate. To securely fasten the cover plate to the chamber, eight stainless steel screws, 1/16 inch in diameter, were utilized.

The three solid state thermoelectric cooling devices mounted on the outside of the chamber were produced by the Melcor corporation and were utilized to remove the heat from the condenser. The cooling devices were normally operated at 2.0 volts and 0.4 amps. Reference 10 contains the cooling devices technical data and operation curves.

6. Heaters

To degas the FC-72 liquid and control the bulk temperature of the liquid, three strip heaters were employed. The heaters are 125mm x 11mm. The strip heaters were secured to the base of the chamber with an Omega Bond 100 Epoxy. The heaters were orientated in a horizontal fashion. The heaters were used to simultaneously raise the bulk fluid temperature to saturation and to degas the fluid. The heaters were operated at 20 volts and 1.8 amps. Once the fluid was degassed, the center heater was secured and the outside heaters were set to 16 volts and 1.2 amps. This maintains the entire chamber's fluid at near saturation temperature and minimizes stratifications.

7. Thermocouples

A total of twelve copper-constantan type thermocouples with a wire diameter of 0.005 inches (0.127mm) were used for temperature measurements. The first two thermocouples were bonded to the inside of the condenser surface using OMEGA Bond type 101 thermally conductive epoxy. The third thermocouple was mounted on the back of the substrate and was used to estimate the heat loss through the rear of the substrate. The forth through seventh thermocouple were glued to the substrate surface. The first two thermocouples were mounted even with the middle row of chips. The second two thermocouples were glued even with the bottom row of chips. These four thermocouples were used to measure the heat losses from the substrate. The ninth through twelfth thermocouples were suspended in the fluid between the substrate board and the heater. The ninth and tenth were suspended 4.5 inches above the floor of the chamber, with the eleventh and twelfth placed 3.5 inches above the floor of the chamber. These locations corresponded to the height of the top and bottom chip rows on the face of the substrate respectively.

B. INSTRUMENTATION

In the design and assembly of the experimental apparatus, seventeen channels were wired and instrumentation provided to measure voltage drops at select points. Additionally channels zero to eleven were used to measure the voltages of the twelve thermocouples. These temperatures were used to calculate heat loss through the substrate, the bulk fluid temperature, condenser temperature and ambient temperature in the chamber. Channel fifty-four measured the voltage drop across the platinum wire. Channel fifty-five through fifty-nine measured the temperature of chips 6,8,5,4 and 2 respectively. The chip temperature sensors were powered at a constant 1 milliamp current. The temperature of the five chip's were obtained from the five temperature vs voltage curves calibrated prior to the beginning of the experiment. Channels sixty through sixty-four measured the voltage drop across the five 2.0 Ohm precision resistors, 1-5 respectively. Channel sixty-five measured the voltage drop across chips 1,4 and 7. Channel sixty-six through sixty-eight measured the voltage drop across the chips 2,5, and 8 respectively. Channel sixty-nine measured the voltage drop across chips 3,6 and 9. Channel seventy measured the voltage drop across the 0.487 precision resistor wired in series with the platinum wire. The current feed to the various chips and the platinum wire was calculated by dividing the voltage drop across the precision resistors by the value of its resistance. The voltage drop across the component and the value of the current were used to calculate the power dissipated and the components heat flux. Table 1 contains a list of the measured resistance and the resistors standard deviation for the six precision resistors. The five 2.0 Ohm precision resistors were used in the previous study. Consequently the measured resistance and standard deviation for resistors 1 to 5 was taken from Reference 4, PP. 7.

Table 1. MEASURED RESISTANCE VALUE FOR SIX PRECISION RESISTORS

Resistor Number	Measure Resistance 20 Sample Average	20 Sample Std Dev
1	1.9994 Ohm	0.0009 Ohm
2	2.0076 Ohm	0.0005 Ohm
3	1.9998 Ohm	0.0003 Ohm
4	2.0018 Ohm	0.0013 Ohm
5	2.0025 Ohm	0.0008 Ohm
6	0.4892 Ohm	0.0000 Ohm

1. Electronic Component

The electronic component used in the experiment consisted of nine Texas Instrument NWSC-EAL #00040TF chips mounted on a ceramic substrate. The electronic component was mounted on the insert board using a 732 RTV adhesive/sealant. The electronic component contains a 3X3 array of chips. The electronic component has eighteen leads connected to it. The electronic component was mounted inverted so that the leads from the chip would not effect the plume before it impinges on the chips. The chips are thus numbered sequentially from right to left, and bottom to top. Thus the top row's three chips are numbered 7,8,9 and the bottom rows chips are numbered 1,2,3. The chips in the left column, 9,6,3, and the chips in the right column 7,4,1 must be powered to the same level since they are connected in parallel. The chips in the center column can be powered individually. The experiments were conducted with all of the chips powered in parallel. The chips are equipped with temperature sensors. The temperature sensors are powered by a constant 1.0 milliamp current. The resistance of the chip varies with temperature. Thus the output voltage of the chip varies with temperature. The temperature of the chip was determined by utilizing the temperature versus voltage calibration curves. As the temperature of the chip increased the voltage of the chip decreased by approximately 1.9 millivolts per degree C. The substrate was mounted on the insert board using a 732 RTV adhesive/sealant.

The chip and its temperature sensor are encapsulated in a small box with a lid. The chip and its temperature sensors are mounted on the base of the box. The chip is then encapsulated by four walls and a thin brass lid. Between the chip and the lid a small air gap exists which increases the thermal resistance to heat transfer. Figure 9 contains a sketch of the chip, air gap and the lid.

2. Power Supplies

The power supplies utilized were very similar to those used by Egger [Ref. 4, pp 8]. The following power supplies were utilized and their primary function listed.

a. Hewlett Packard 6214C 0-10 volts/0-1 amps: Used to power the thermal electric coolers.

b. Kepco Power Supply 0-100 volts/0-5 amps: Used to power the nine chips.

c. Hewlett Packard 6286A 0-20 volts /0-10 amps: Used to power the strip heaters which were used for degassing and bulk fluid temperature maintenance.

d. WP711 0-40 volts / 0-1 amps: Used to power the platinum wire.

3. Data Acquisition System

A Hewlett Packard 3497A data acquisition system was used to obtain the necessary measurements, and an Hewlett Packard 300 desk top computer was used to control the HP3497, record the measurements and reduce the data.

The HP3497A utilized the following insert boards.

a. One standard HP 44422A 20 Channel T-Couple Acquisition board used to measure the twelve thermocouple's voltage.

b. Two modified HP 44422A 20 Channel T-Couple Acquisition Boards. The first was used to measure the five voltage drops across the chip's temperature sensors and the voltage drop across the platinum wire. The second unit was used to measure the six voltage drops across the precision resistors and the five voltage drops across the chips

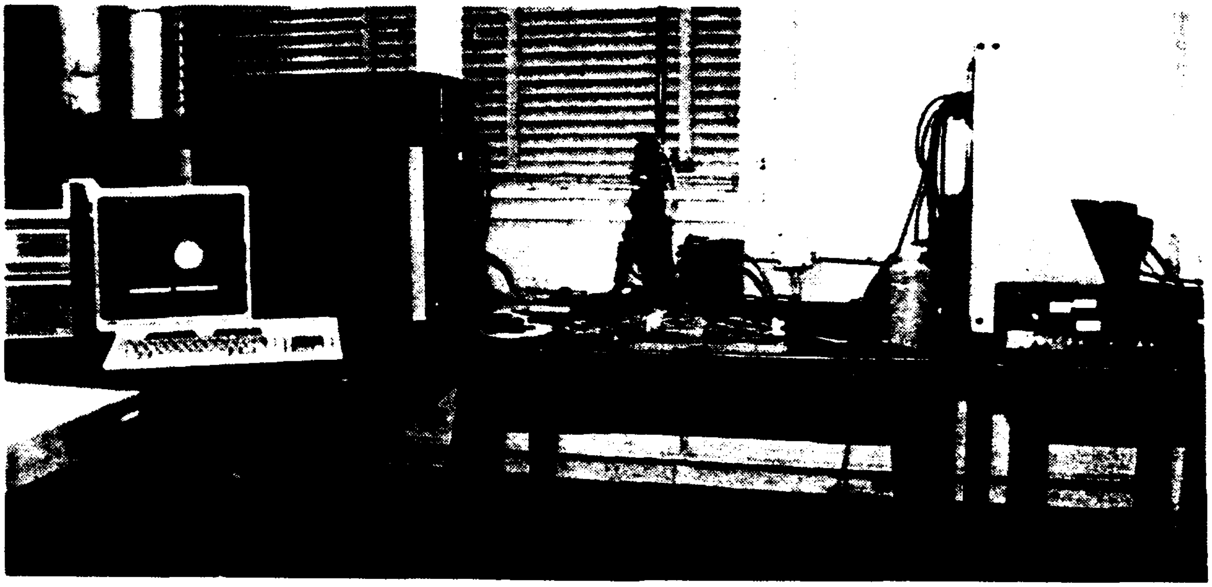

FIGURE 2. EXPERIMENTAL APPARATUS PHOTO

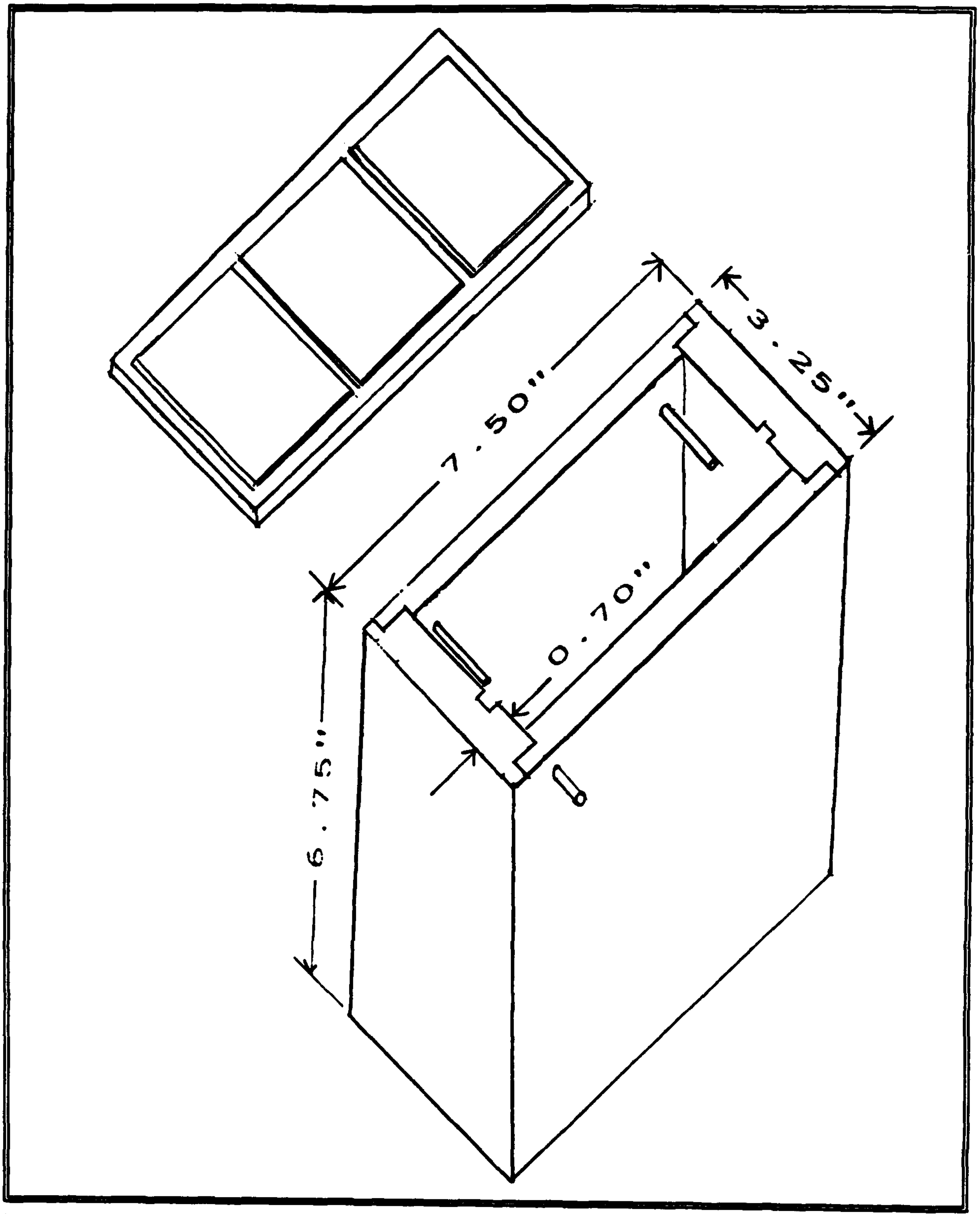

FIGURE 3. EXPERIMENTAL CHAMBER ISOMETRIC

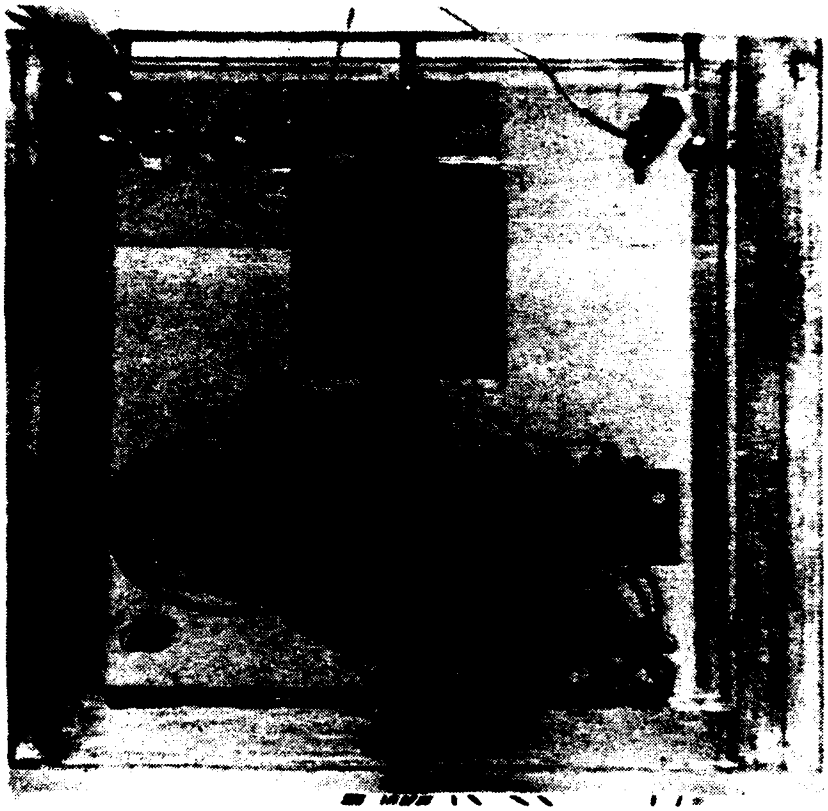

FIGURE 4. CHAMBER WITH INSERT BOARD AND PLATINUM WIRE

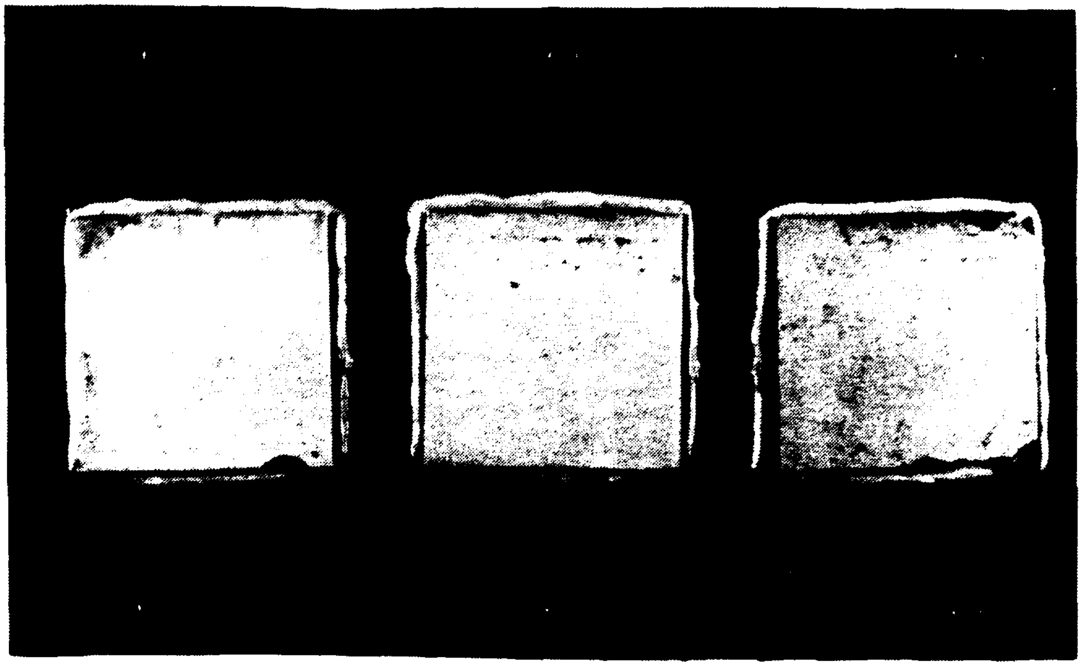

FIGURE 5. CONDENSER SURFACE WITH ELECTRIC COOLERS

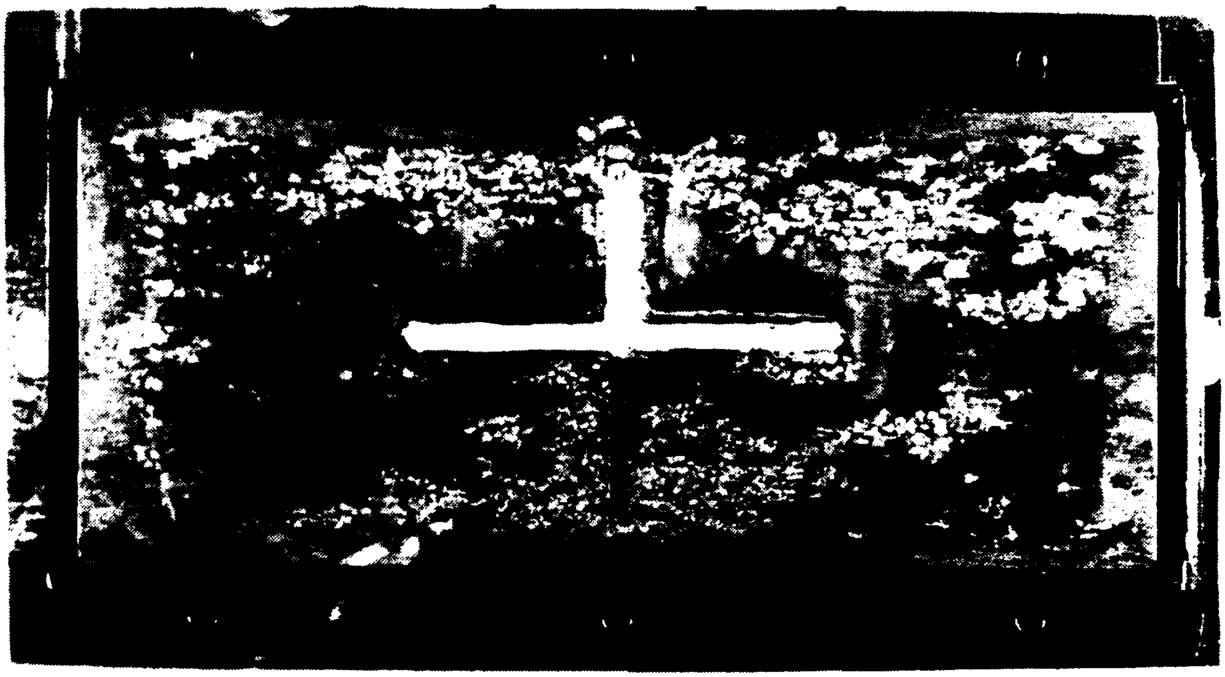

FIGURE 6. INSIDE OF CONDENSER SURFACE

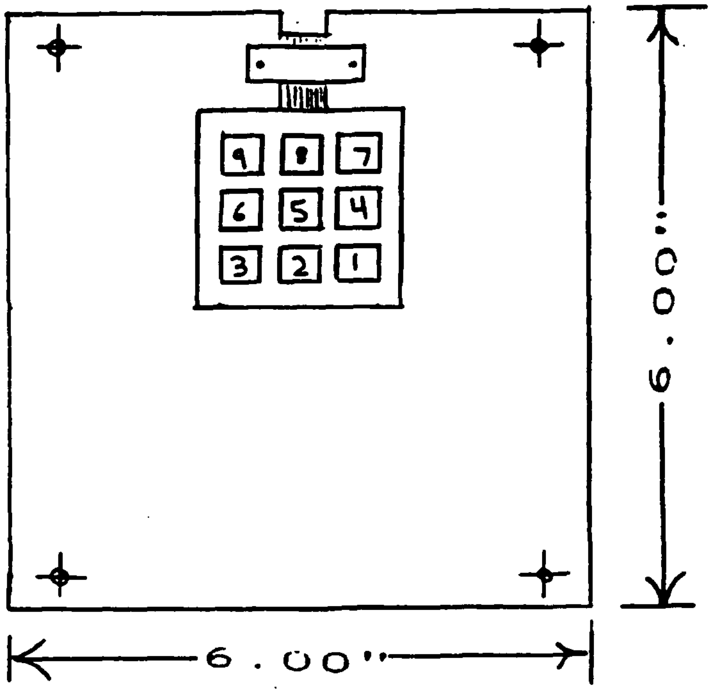

Figure 7 Insert Board

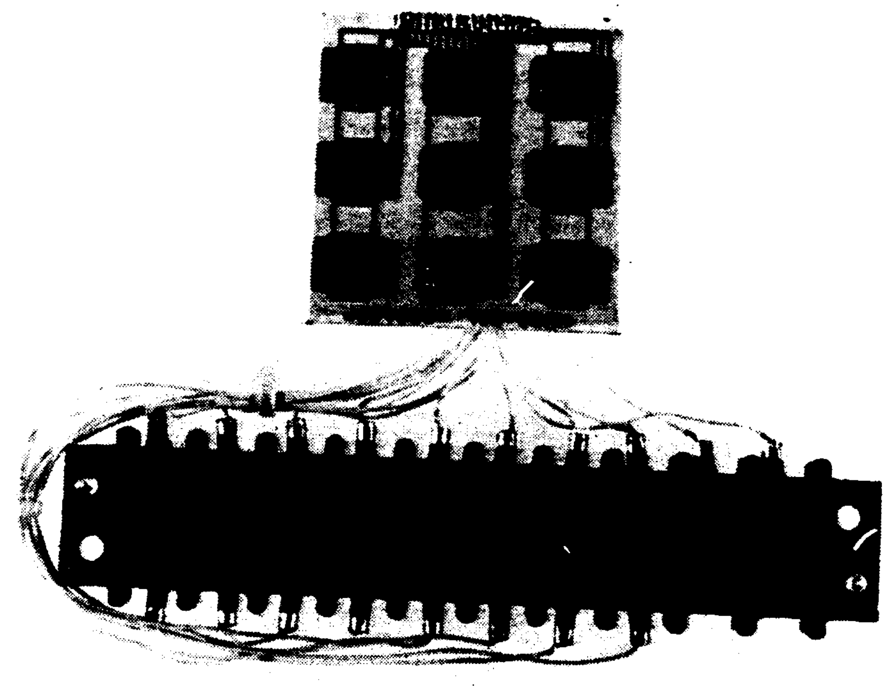

FIGURE 8. INSERT BOARD WITH ELECTRONIC COMPONENTS LIDS ON

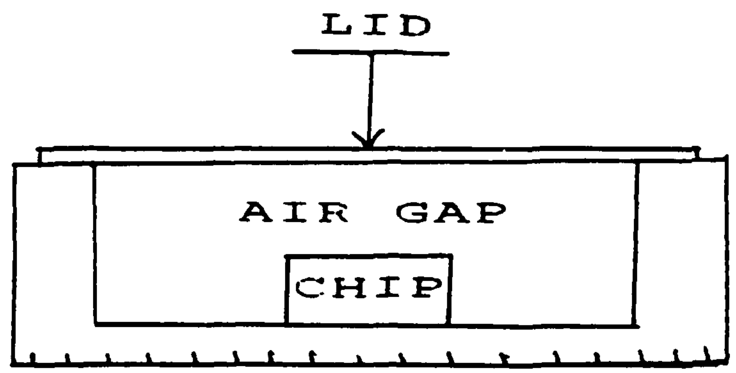

FIGURE 9. ELECTRONIC CHIP SCHEMATIC

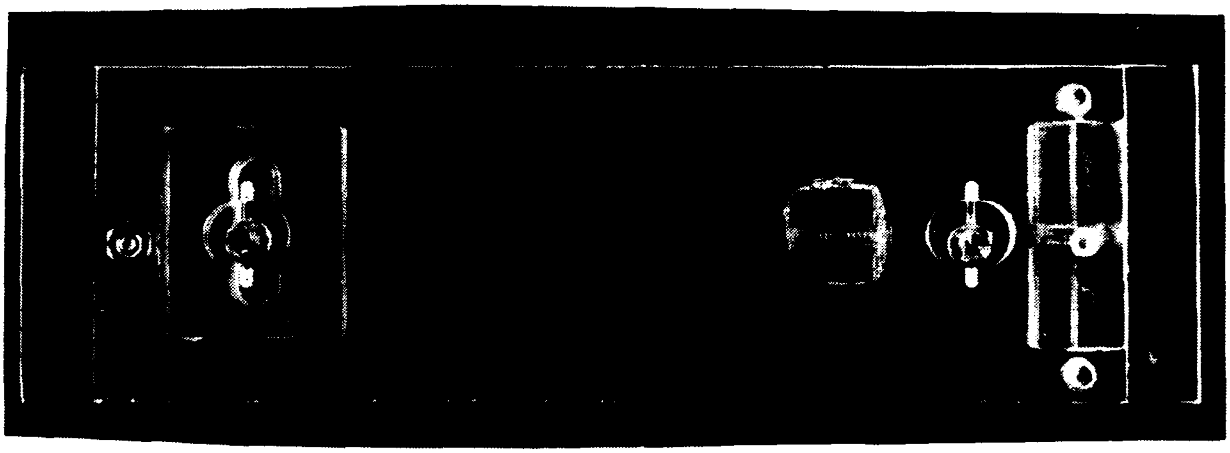

FIGURE 10. PLATINUM WIRE

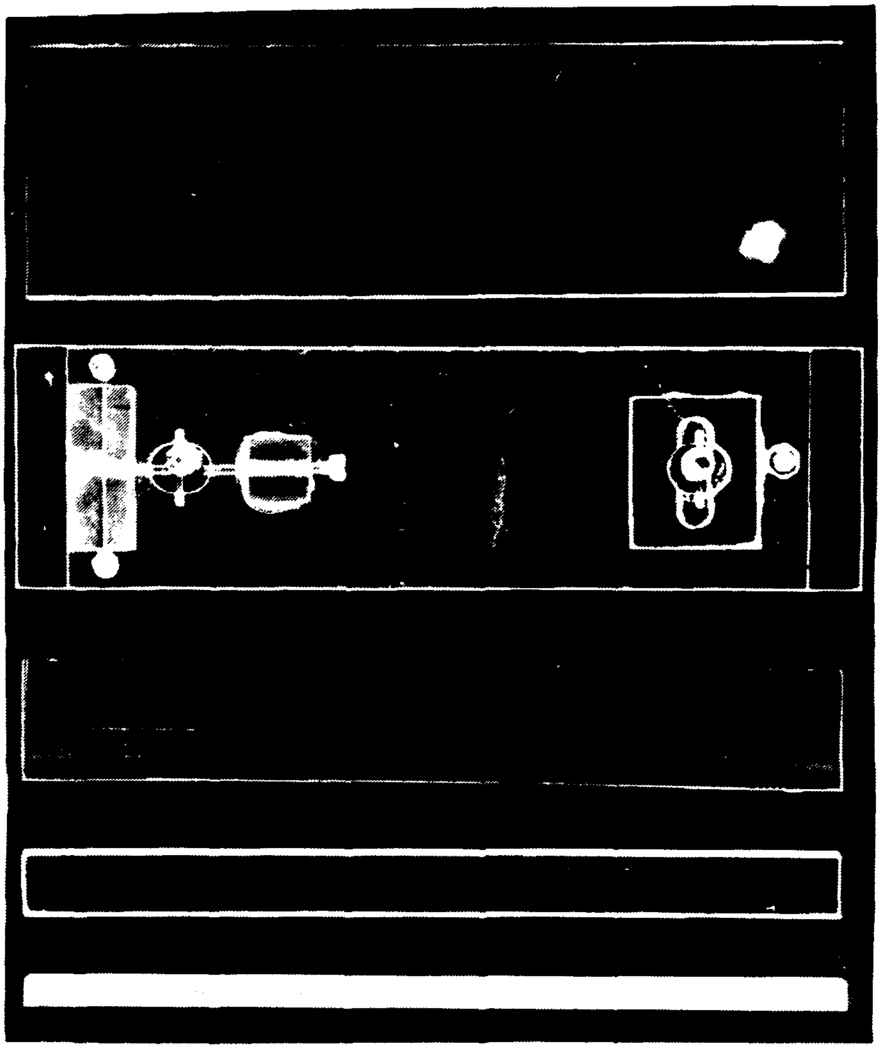

FIGURE 11. PLATINUM WIRE AND FOUR SPACES

FIGURE 12. ELECTRONIC COMPONENT WITH LIDS REMOVED

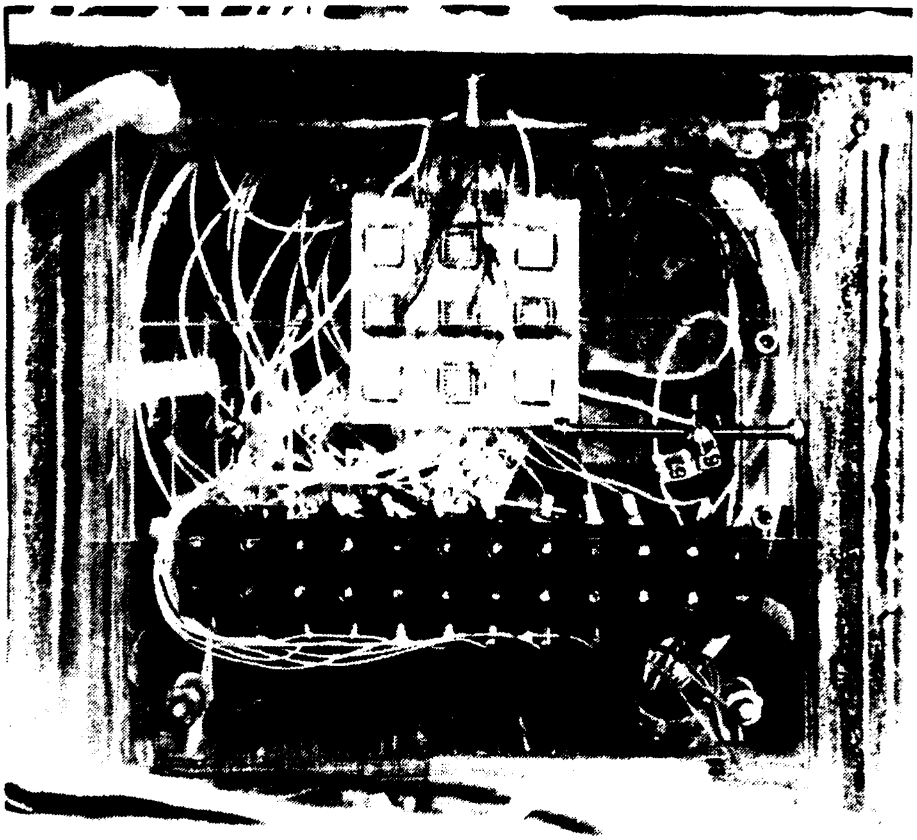

FIGURE 13. CHAMBER DURING EXPERIMENTAL RUN

III. EXPERIMENTAL PROCEDURE

A. PREPARATIONS

Meticulous care was required to obtain high quality data. The first set of experiments was conducted on chips with lids, which were immersed in fluid which contained disolved gasses. The next set of experiments was conducted on chips with lids, which were immersed in a fluid which was degassed. The third set of experiments was a repeat of the first with the exception that the lids from the chips were removed. Similarly, the forth and last set of data was a repeat of the second set of experiments without lids. All four sets of these experiments were conducted with the heat flux from the platinum wire varying from 0 KW/m^2 to approximately 260 KW/m^2 and the power settings of each chip varying from 0.3 Watts to approximately 3.0+ Watts.

B. PROCEDURE NUMBER ONE (CHIP IMMERSED IN FLUID WHICH CONTAINS DISSOLVED GASSES)

1. Verify the fluid level is above the top of the substrate and below the 0.25 inch overflow tube at the top of the chamber.

2. Attache the thermal insulating blanket to the chamber.

3. Power the two HP-3497 data acquisition units.

4. Power the HP300 series desk top computer and load the data acquisition program listed in Appendix D.

5. Power the thermo electric coolers, set the HP6282A DC power source at 2.0V and 1.3A.

6. Power the nine chips of the substrate using the HP-6289A power source.

7. Verify that the power to the platinum wire is initially secured.

8. Initially set the power source to the chips to 0.30 Watts. Check the output of the data aquisition program to determine if the chips have reached steady state. If the chips have reached steady state, record the data and then increase the power to the chips by approximately 0.7 Watts. Continue this process until the power dissipated across the chip reaches 3.0+ Watts and 120 degrees Celsius. Do not raise the chip power setting above this point to prevent damaging the chip.

9. Lower the power feed to the chips by approximately 0.7 Watts. When the chip reaches steady state, record the data and then decrease the power to the chips by approximately 0.7 Watts. Continue this process until

the chips power settings have returned to approximately 0.3 Watts.

10. Increase the heat flux to the platinum wire to approximately 160 KW/m^2. Repeat steps 8 and 9.
11. Increase the heat flux to the platinum wire to approximately 210 KW/m^2. Repeat steps 8 and 9.
12. Increase the heat flux to the platinum wire to approximately 260 KW/m^2. Repeat steps 8 and 9.
13. Secure power to the platinum wire and the chips.

    Note: The first and third portion of the experiment were conducted on fluid which contained dissolved gasses. The first portion of the experiment was conducted without step 9. This step was subsequentally added to verify that a boiling curve loop actually did not exist.

C. PROCEDURE NUMBER TWO (CHIPS IMMERSED IN DEGASSED FLUID)

1. Verify the fluid level is above the top of the substrate and below the 0.25 inch overflow tube at the top of the chamber.

2. Attache the thermal insulating blanket to the chamber.

3. Power the two HP-3497 data acquisition units.

4. Power the HP300 series desk top computer and load the

data acquisition program listed in Appendix D.

5. Set the HP6282A DC power source for the thermo electric coolers to 2.0V and 1.3A.

6. Set the Kepco power supply for the strip heaters to 20V and 1.8A. Once fluid has reached saturation temperature and is rapidly boiling, 56 degrees Celsius, hold for two hours to ensure proper degassing of the fluid.

7. Once the required degassing is accomplished, power to the strip heaters is reduced to 1.2 amps and 16V. This will keep the fluid degassed and at saturation temperature.

8. Set the power level of the chips to approximately 0.3 Watts.

9. Verify that the power to the platinum wire is initially secured.

10. Check output of data aquisition program to see if chips have reached steady state. When steady state is reached, activate the data acquisition program to record the data, and increase the chip power setting by approximately 0.7 Watts.

11. Repeat step 10 until the chips are dissipating 3.0+ Watts of power and the chip's temperature has reached approximately 120 degreees Celsius.
12. Lower the power feed to the chip by approximately 0.7 Watts. Check the output of the data aquisition program to determine if the chips have reached steady state. When the chips reach steady state, activate the data aquisition program to record the various readings.
13. Repeat step 12 until the chips power settings are approximately 0.3 Watts.
14. Increase the heat flux to the platinum wire to approximately 160 KW/m^2. Repeat steps 10-13.
15. Increase the heat flux to the platinum wire to approximately 210 KW/m^2. Repeat steps 10-13.
16. Increase the heat flux to the platinum wire to approximately 260 KW/m^2. Repeat steps 10-13.
17. Secure power to the platinum wire and the chips.

Note: Steady state was determined by two different procedures. The chips with lids would generally steady out to a constant value. Steady state was determined when the chip's temperature varied by less than 0.1 degrees Celsius over a ten minute period. The chips with the lids removed, generally fluctuated over up to a 1.0 degree temperature range when the reached steady state. Over a five minute period, three sets of data were recorded. If four out of the five chips temperature either remained fairly constant or oscillated up and down, steady state was concluded. The temperature of each component at the particular power setting was determined by averaging the three temperature values recorded for the respective component. If the chip's temperatures were either steadily increasing or decreasing over each of the three data sets, the chip had not reached steady state. A ten minute wait was allowed before the next set of three data sets was obtained. Only when the temperature values of at least four of the five components were either remaining fairly constant or oscillating up and down would steady state be concluded.

D. DATA REDUCTION

Data that was obtained from the actual experimental apparatus were three voltage measurements per chip, two voltage measurements for the platinum wire, and twelve thermocouple temperature measurements. The data was reduced by the computer program, contained in Enclosure D, and was subsequently plotted out to visually present the results.

1. Power Drop Across the Chip

Power1= Volt1*Volt2/Resist1

where Volt1 and Volt2 are the voltages across the chip and the precision resistor, and Resist1 is the resistance of the precision resistor.

2. Heat Flux Across the Chip

Flux1= Power1/Area1

Power1 is the power drop across chip 2 and the Area1 is equal to the length times width of the chip face.

3. Power Drop Across the Platinum Wire

Power2=Volt3*Volt4/Resist2

Volt3 is the voltage drop across the Platinum wire, Volt4 is the voltage drop across the precision resistor, and Resist2 is the resistance of the precision resistor.

4. Heat Flux Across the Platinum Wire

Flux2 = Power2/Area

Power2 is the power drop across the platinum wire and the Area is equal to pi times the length times the diameter of the wire.

5. Calculated Thermocouple Output Temperature

T(I) = 1.0/(A + B/Volt(I))

A and B are constants equal to 0.0008011067 and 0.00003961586 respectively. These two values were determined during the calibration procedure.

$$T(I) = 1.0 / (0.0008011067 + 0.00003961586/0.001) = 24.74$$

Celsius

6. Calculating Output Voltage Across the Chip

$$T= C + D*Voltage5$$

Where C and D are constants which are which were determined during the calibration procedure and Voltage5 is the voltage drop across the temperature sensor.

7. Bulk Fluid Temperature

$$Tbulk = (T1 + T2 + T3 + T4)/4.0$$

Where T1, T2, T3, and T4 are the temperatures of the four thermocouples suspended in the fluid.

IV. RESULTS AND DISCUSSIONS

The data obtained can be grouped for discussion into four different categories:

A. Heat transfer results for chips with lids versus chips without lids.

B. Heat transfer results for chips immersed in degassed fluid versus chips immersed in fluid which contained dissolved gasses.

C. The effects of varying the platinum wire heat flux on chips' temperature.

D. The effects of the hysteresis phenomenon on the heat transfer from the chips.

Additionally the chips without lids were examined the the microscope. These five chips were compared to two chips whose lids were removed after the experiment. The findings of this examination are discussed in the following category:

E. Damage to the Chip.

A. LIDS ON VERSUS LIDS REMOVED

All seven of the graphs, Figures 17-23, plot the power dissipated per chip as a function of the temperature difference between the chip and the fluid. The graphs contain plots for chips with and without lids. By removing the lids, the chips on average, were able to operate at 168% of the power level they operated at with the lids on, while maintaining a constant 50.0 Celsius of temperature difference between the chip and the fluid. Table 2 is a summary of this data. The higher heat transfer rate for chips without lids occurred not only for the chips immersed in the degassed fluid but also for the chips immersed in the fluid which contained dissolved gasses. It also occurred for all platinum wire heat flux settings.

TABLE 2 PERCENTAGE OF IMPROVEMENT OBTAINED BY REMOVING LIDS

FIGURE	PWR AT 50 C SUPERHEAT LIDS OFF(WATTS/CHIP)	PWR AT 50 C OF SUPERHEAT LIDS ON(WATTS/CHIP)	IMPROVEMENT
1	3.12	1.86	68.0%
2	3.05	1.81	69.0%
3	3.12	1.83	70.0%
4	2.95	1.75	69.0%
5	2.81	1.73	63.0%
6	3.12	1.87	67.0%
7	2.95	1.75	69.0%
AVG	3.02	1.80	68.0%

B. DEGASSED FLUID VERSUS FLUID *WITH DISSOLVED* GASSES

Figures 17-19 are graphs of power dissipation form Chips 2,4, and 5 versus the temperature difference between the chip and fluid. The fluid used in this portion of the experiment contained dissolved gasses. Chip 5 is the center chip in the 3X3 array. Chip 4 is the far right chip in the middle row. Chip 2 is the middle chip in the bottom row as shown in Figure 7. At chip power settings, greater than 1.4 Watts, the data for the chips with and without lids was quite linear. At chip power settings below 1.4 Watts, the data for the chips without lids is not linear. At these power settings, the fluid which contained dissolved gases was at a temperature below the saturation temperature. The heat was dissipated from the chips both by convection and subcooled boiling. While the intensity of the plume from the platinum wire increased as it passed over each successive row of chips, the temperature of the fluid increased at a greater rate. Thus, the temperature of the chips in the middle rows had to increase to achieve a similar temperatures difference and remove roughly the same amount of heat.

Figures 20-23 contain the data for the chips immersed in the degassed fluid. The plots were all very linear. The data for the chips with and without lids was closely grouped regardless of the power setting of platinum wire. With the fluid held at saturation temperature, boiling was the chief mechanism for heat removal from the chips. At low temperature differences between the chip and the fluid, for instance 10.0 degrees Celsius, the chips without lids dissipated approximately 30.0 percent more power than the chips with lids. As the temperature difference between the chips and the fluid increased, to approximately 50.0 degrees Celsius, the chips without lids were able to dissipate approximately 68.0 percent more power than those with lids.

In all cases, both the fluid which contained dissolved gasses, Figures 17-19, and the fluid which was degassed, Figures 20-23, the chips with lids generally had very linear data. The chips immersed in the degassed fluid were slightly warmer than the chips immersed in the fluid which contained dissolved gasses at the same power settings. Figures 24-29 contains the plots of the chips immersed in degassed fluid and the chips immersed in the fluid containing dissolved gasses. The figures for the chips without lids contains graphs which are slightly spread apart. However, the graphs for the three chips under these condition look very similar. Figures 25,27, and 29 contain the graphs for chips with lids. The plots for the chips with lids are quite different from those without lids. Figures 24, 26 and 28 contain the plots for the chips without lids. This data is very tightly grouped. The chips plots all have relatively the same slope. The chips immersed in the fluid containing dissolved gasses are initially cooler than the chips immersed in the degassed fluid. This is only a temporary condition. After a few hours, the dissolved gasses will come out of solution, and the fluid which initially contained dissolved gasses will become degassed. At this point there will be no difference between the two sets of curves.

C. INFLUENCE OF PLATINUM WIRE HEAT FLUX ON THE CHIP'S TEMPERATURE

The platinum wire had no significant effect on the temperature of the chips with or without lids. This was true regardless of the fluid being degassed or containing dissolved gasses. Figures 17-23 contain plots of the chips power setting versus the temperature difference between the chip and the fluid. At first glance, Figures 17-19 contradict this point. The so called contradiction occurs in the plots with the lids removed, and the platinum wire secured. At a chip power setting of approximately 0.7 Watts, the chips with the platinum wire secured, appear to be much warmer than the chips immersed in the plume from the platinum wire. However, this only occurred at one point. The plots are actually all well within each others uncertainty. At all other chip power settings, the variations of the plots is very small and well within the experimental uncertainty of our measurements. Furthermore, within the uncertainty, there is no clear trend of the chip's being cooler at any particular platinum wire setting. The plume from the platinum wire was simply not needed. At low power settings, the chip's temperature was so low and there was no practical reason to try to augment the heat removal by convection. Furthermore, the plume was found to be ineffective in improving the amount of heat removed from the chip. At high chip power settings, the mechanism for heat removal was boiling. The plume once again played no role in improving the heat removal from the various chips.

D. HYSTERESIS PHENOMENON

Egger found that a constant source of bubble generation from below is an effective way to eliminate the boiling curve overshoot and hysteresis loop associated with dielectric fluids (Ref 4 Pg 44). This study found that these two phenomena did not occur either with the lids on or the lids off, nor did they occur in the degassed fluid or in the fluid which contained dissolved gases. The platinum wire used in Egger's study, was extremely smooth and thus did not contain many nucleation sites. The surface of the chip used in the present study was not as smooth and thus contained a great number of nucleation sites. The geometry of the two studies was also very different. Because of the material was not as smooth, while the conditions to produce these phenomena were present in the previous study, they did not exist in this study.

E. DAMAGE TO CHIPS WITHOUT LIDS

The chips were immersed in the fluid with their lids removed for over three weeks. The chips were operated at various power settings for over 50.0 hours without lids. These power settings included runs in which the chips temperature approached 120 degrees Celsius and over 3.0 Watts of power per chip. These two parameters are the recommended operational limits for the chips. After these runs were completed, the apparatus was disassembled and examined under an optical microscope. The chip surface appeared undamaged. The hairs which connect the chip to the base were all attached and did not appear to be bent. Of the nine chips, five had their lids removed before the experiment and two had their lids removed after the experiment. The five chips which were operated without their lids were compared to the two other chips. Each was examined under the microscope at magnifications of 25 and 250. No signs of damage, discoloration or corrosion was found on any of the five chips which were operated without their lids. For all intents and purposes, all seven chips remained identical. Figures 14-16 contain photos of the chips at these magnifications.

> Note: The temperature sensors were calibrated in an ethylene glycol bath. The fluid in the bath caused some corrosion on the wire leads to the chips. For several weeks, much of the data from chips 6 and 8 was faulty. The data either was several thousand degrees off of the actual temperature or remained constant over all power settings. After several unsuccessful attempts, the corrosion was removed and reliable data was obtained. Consequently, reliable data was recorded and graphs were plotted for chips 2, 4, and 5 for the fluid containing dissolved gasses. The degassed fluid runs were completed after the dissolved gas data runs. Chip 8 produced accurate data for the experiments conducted with the degassed fluid. The data for chips 2,4,5, and

8 was recorded and graphs were plotted for these chips.

FIGURE 14.CHIP 2 LIDS REMOVED PRIOR TO EXPERIMENT,MAGNIFICATION X25

FIGURE 15. CHIP 3 LIDS REMOVED AFTER EXPERIMENT, MAGNIFICATION X25

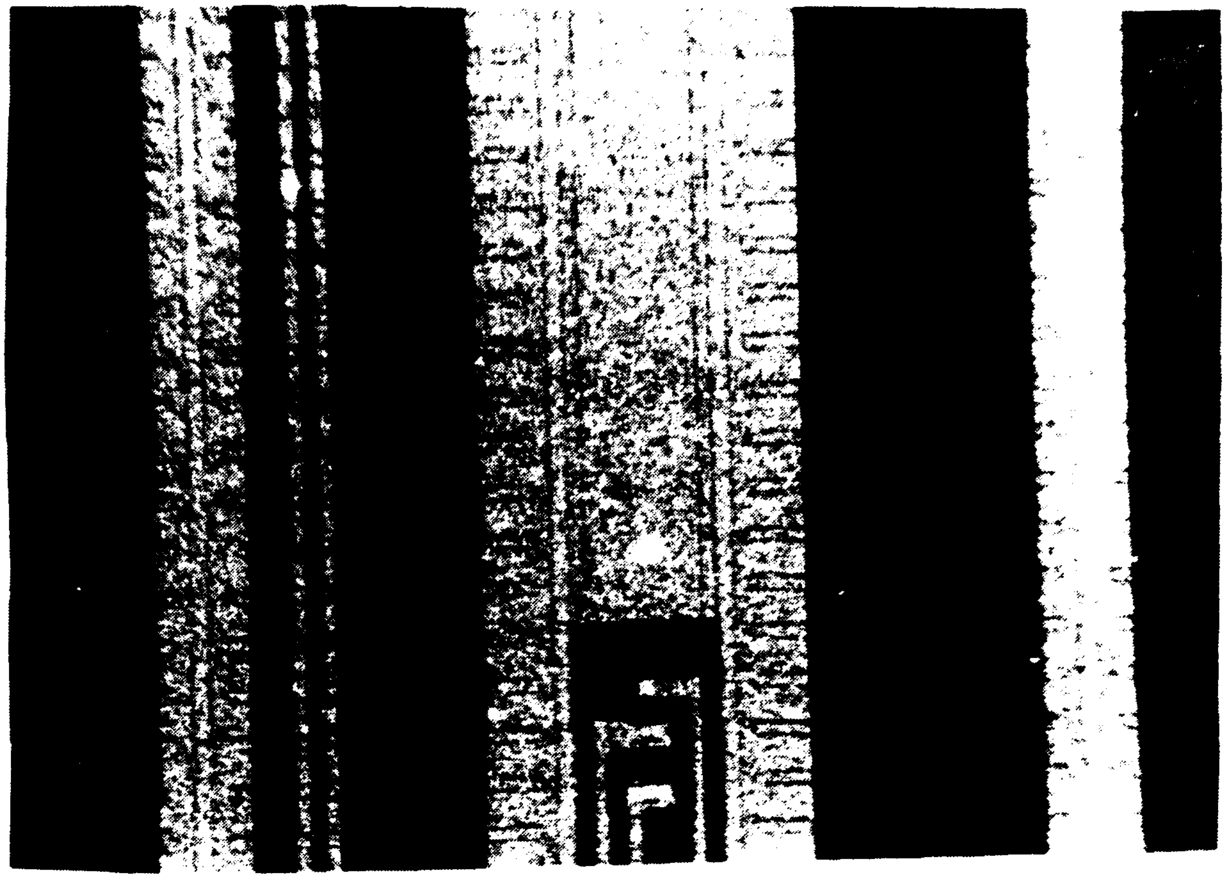

FIGURE 16. CHIP 5,LIDS REMOVED BEFORE EXPERIMENT,MAGNIFICATION X250

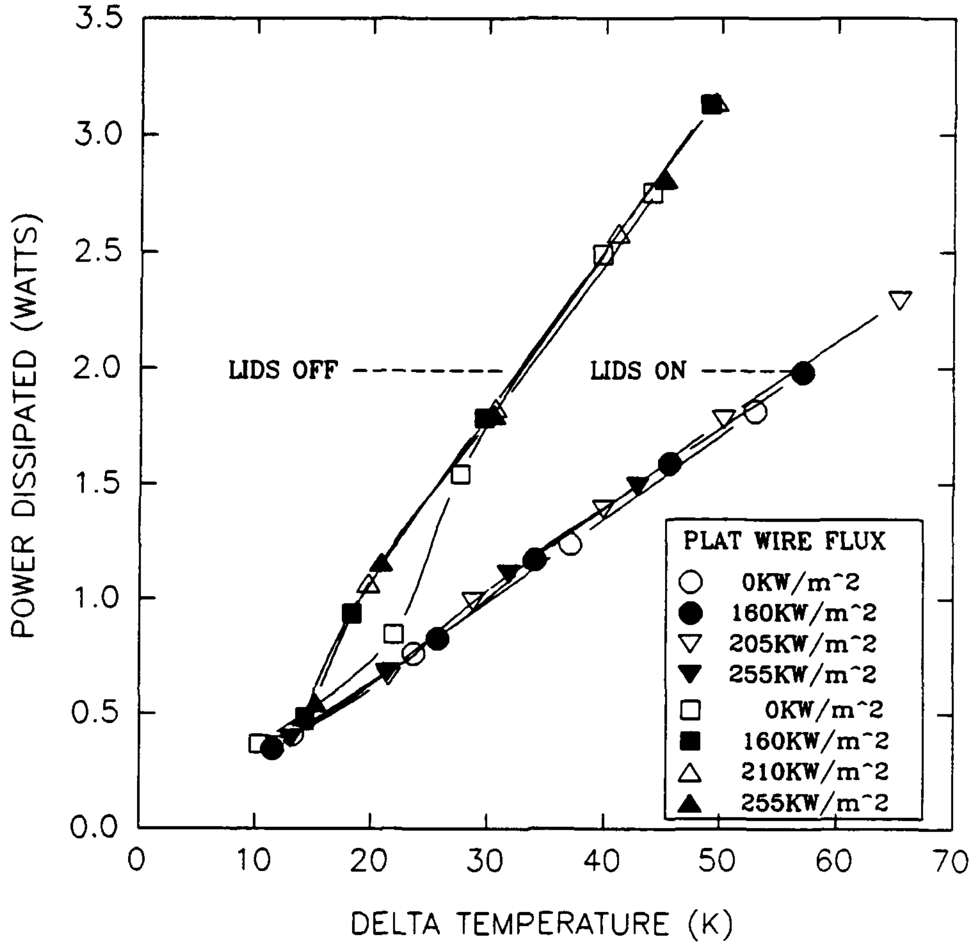

FIGURE 17. CHIP 5, FLUID CONTAINS DISSOLVED GAS, LIDS ON VS LIDS OFF

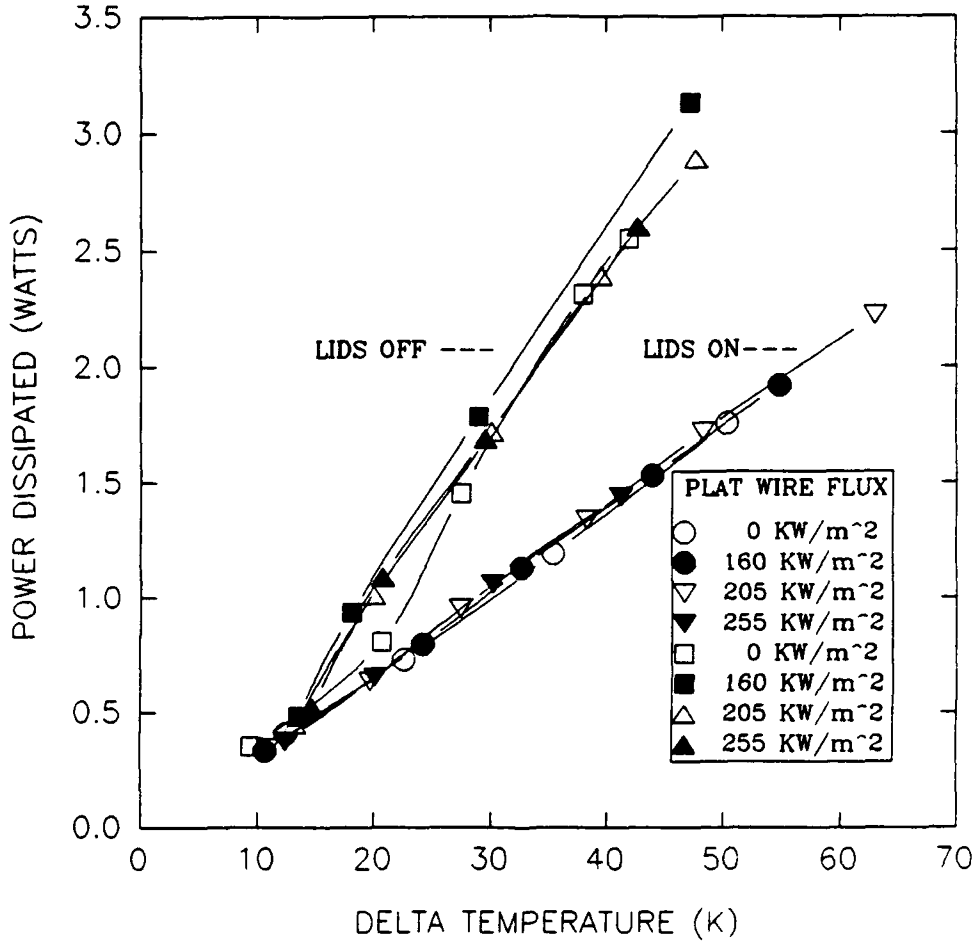

FIGURE 18. CHIP 4, FLUID CONTAINS DISSOLVED GAS, LIDS ON VS LIDS OFF

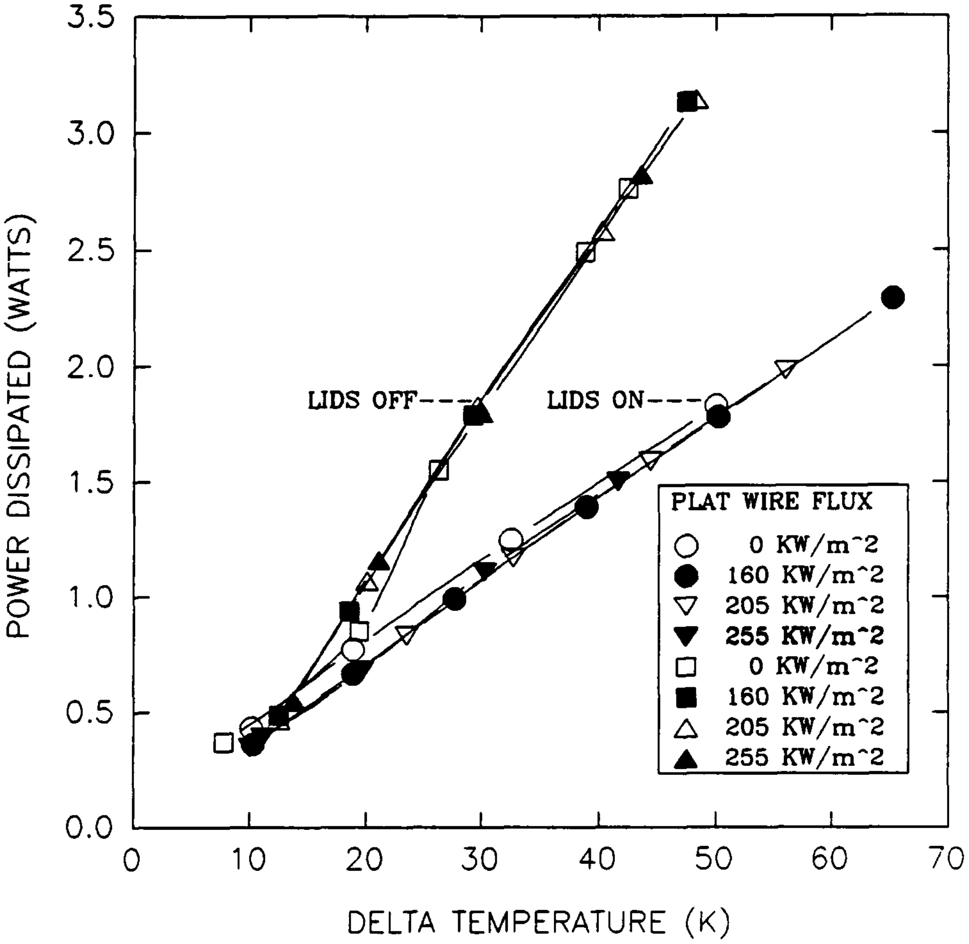

FIGURE 19. CHIP 2, FLUID CONTAINS DISSOLVED GAS, LIDS ON VS LIDS OFF

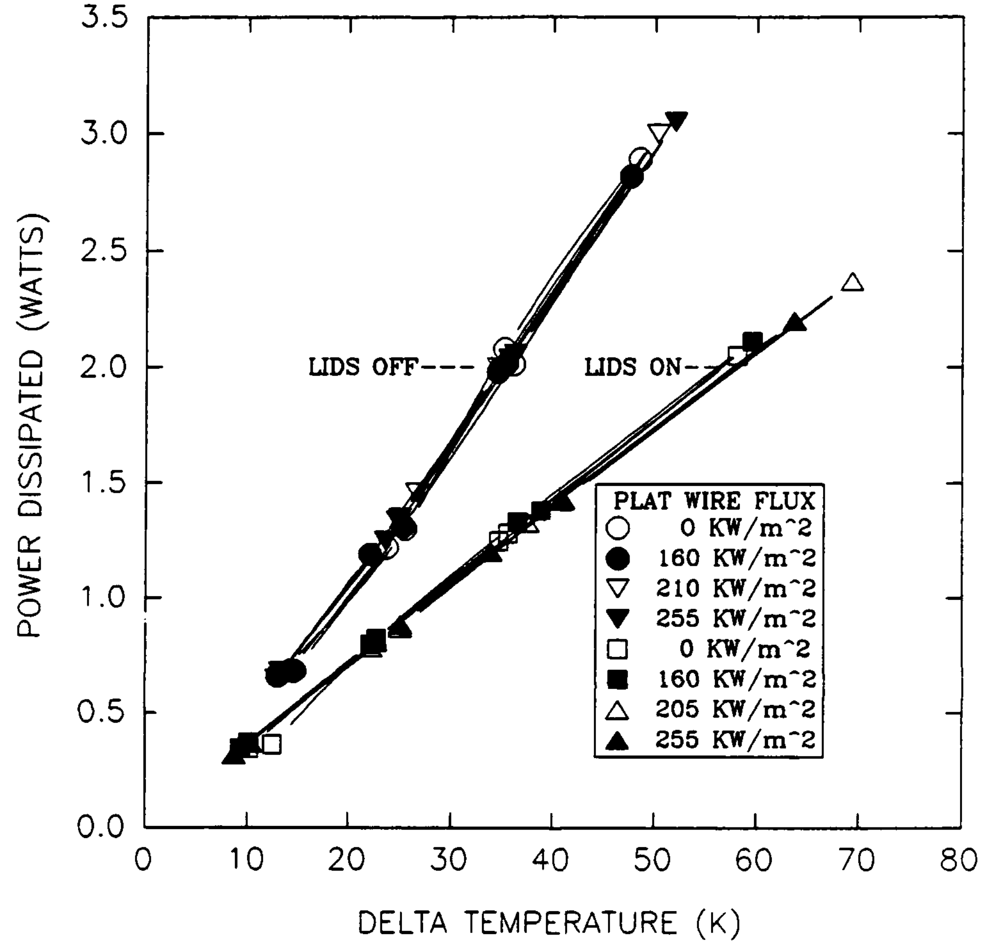

FIGURE 20. CHIP 5, FLUID IS DEGASSED, LIDS ON VS LIDS OFF

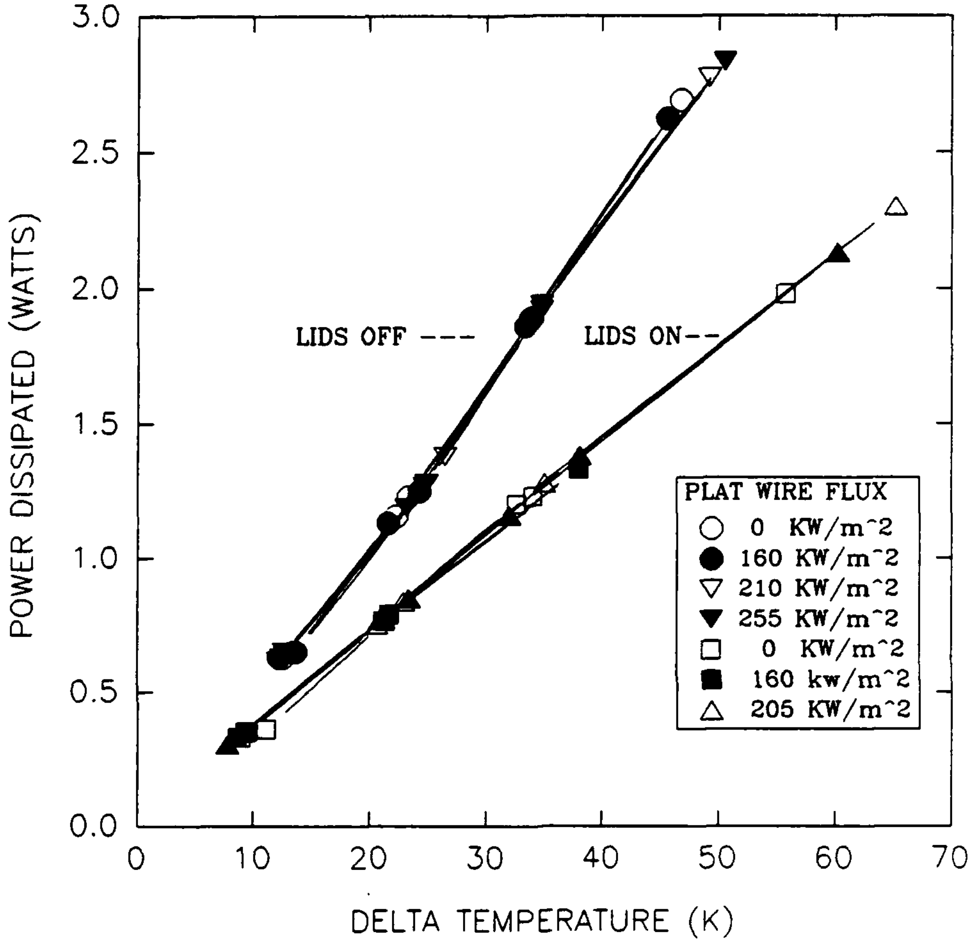

FIGURE 21. CHIP 4, FLUID IS DEGASSED, LIDS ON VS LIDS OFF

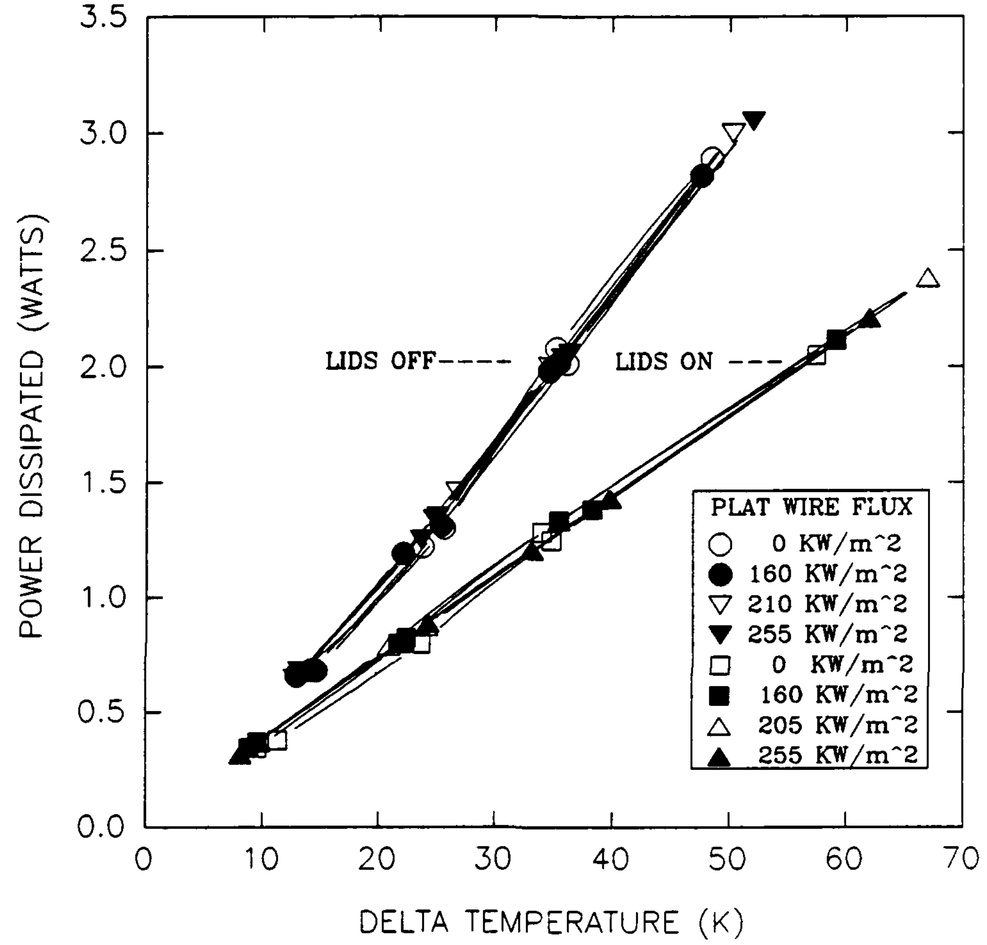

FIGURE 22. CHIP 2, FLUID IS DEGASSED, LIDS ON VS LIDS OFF

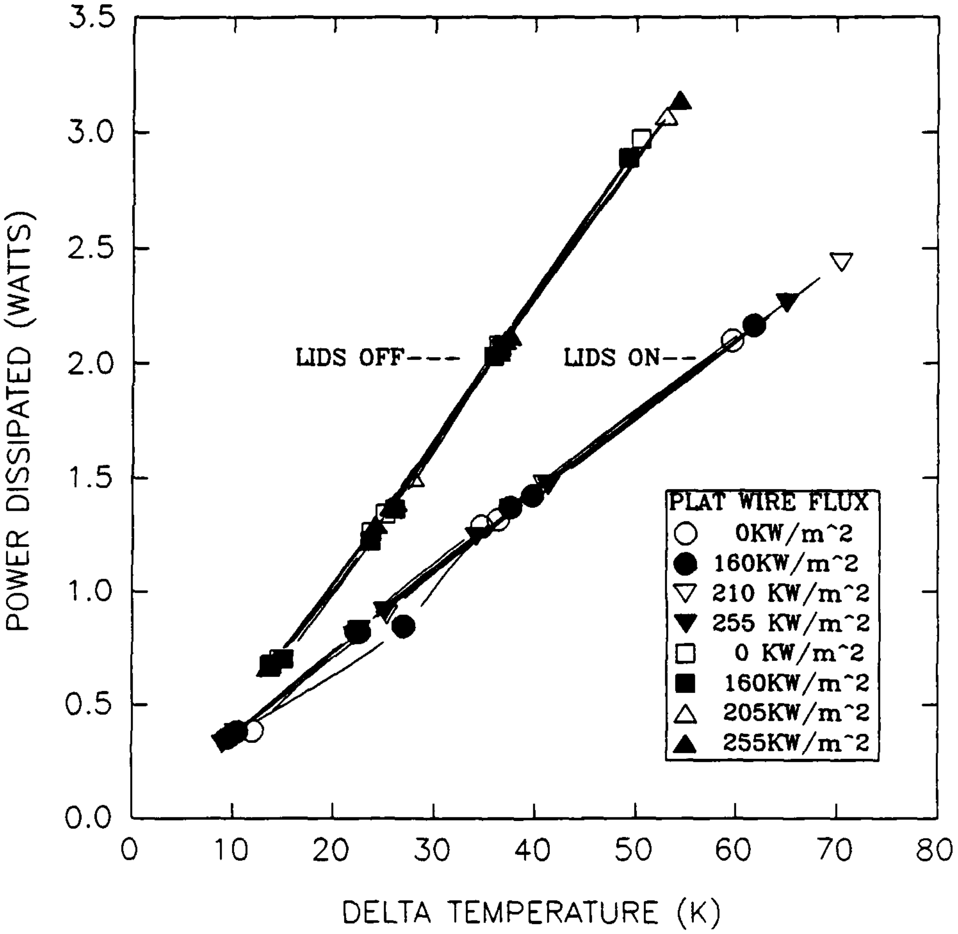

FIGURE 23. CHIP 8, FLUID IS DEGASSED, LIDS ON VS LIDS OFF

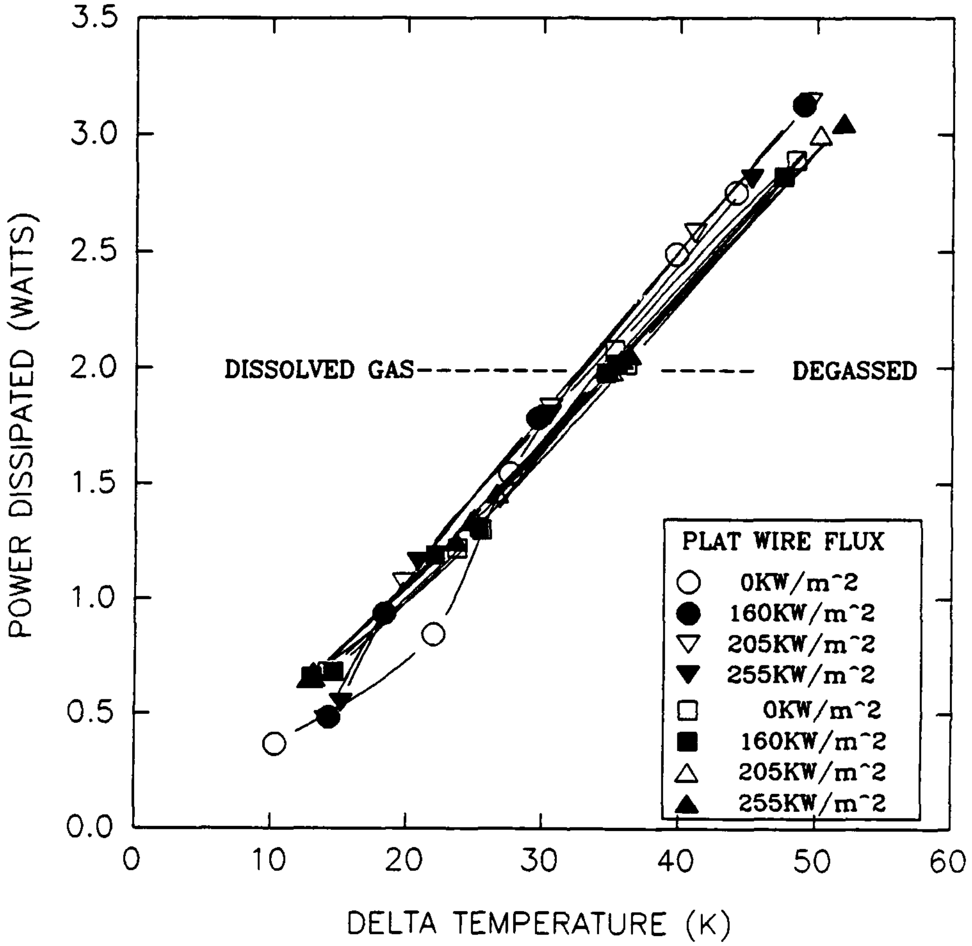

FIGURE 24. CHIP 5, LIDS OFF, DEGASSED FLUID AND FLUID WITH DISSOLVED GAS

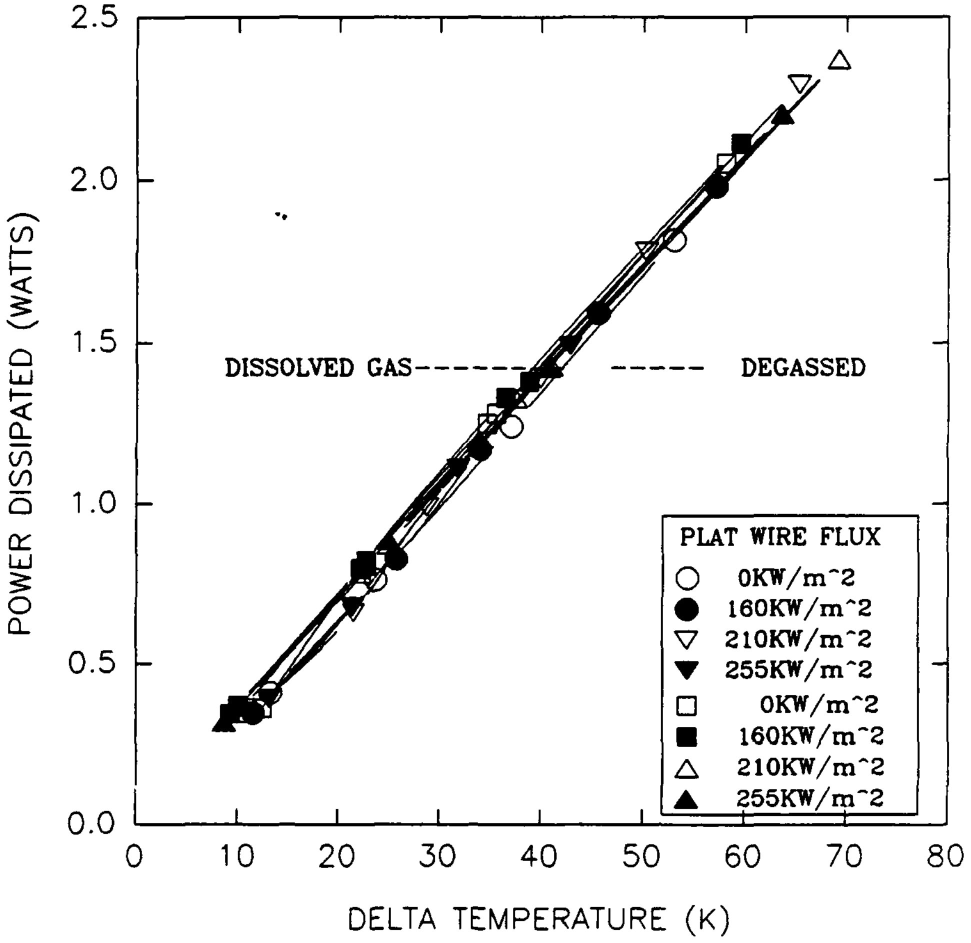

FIGURE 25. CHIP 5, LIDS ON, DEGASSED FLUID VS FLUID WITH DISSOLVED GASSES

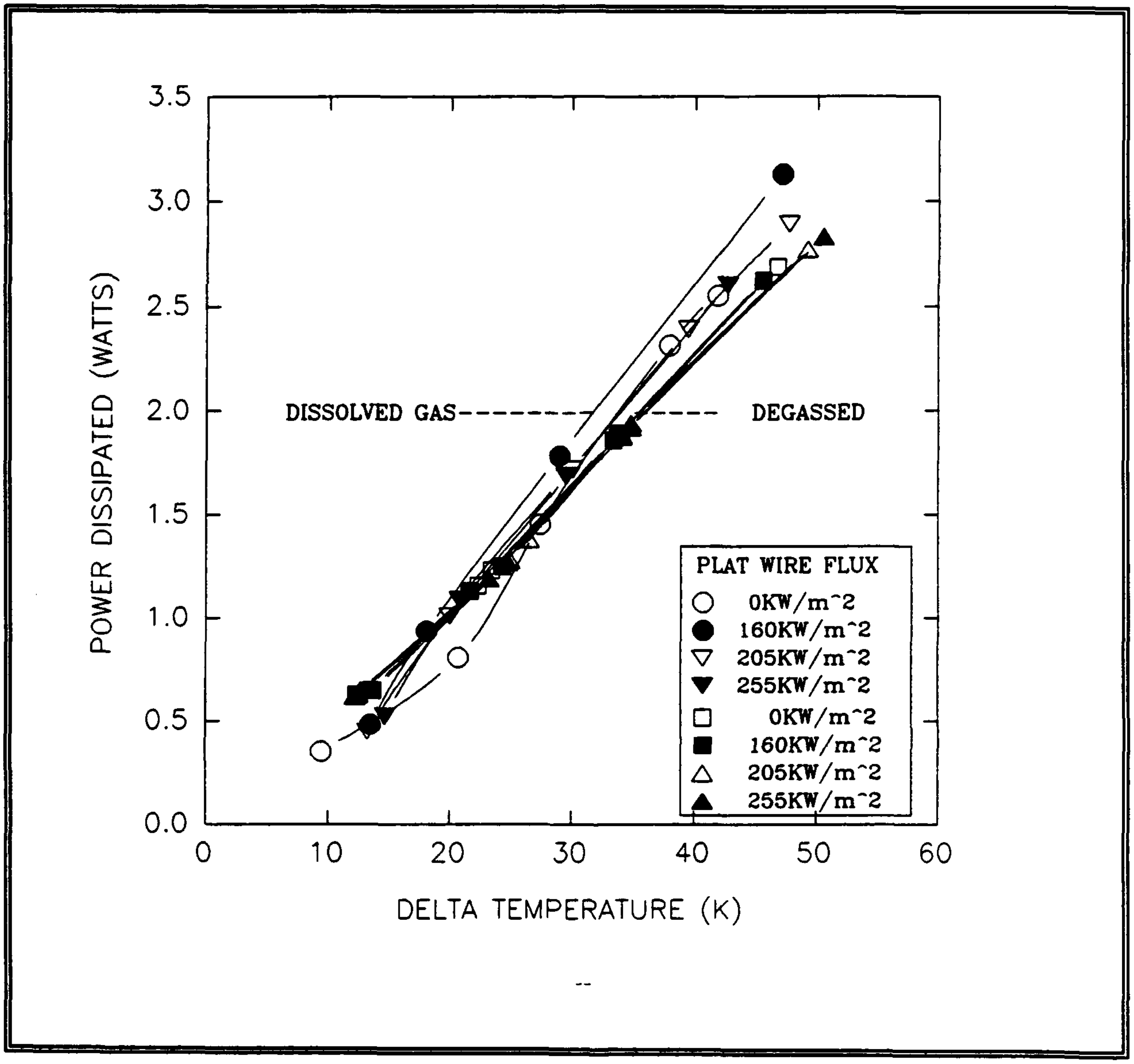

FIGURE 26. CHIP 4, LIDS OFF, DEGASSED FLUID VS FLUID WITH DISSOLVED GASSES

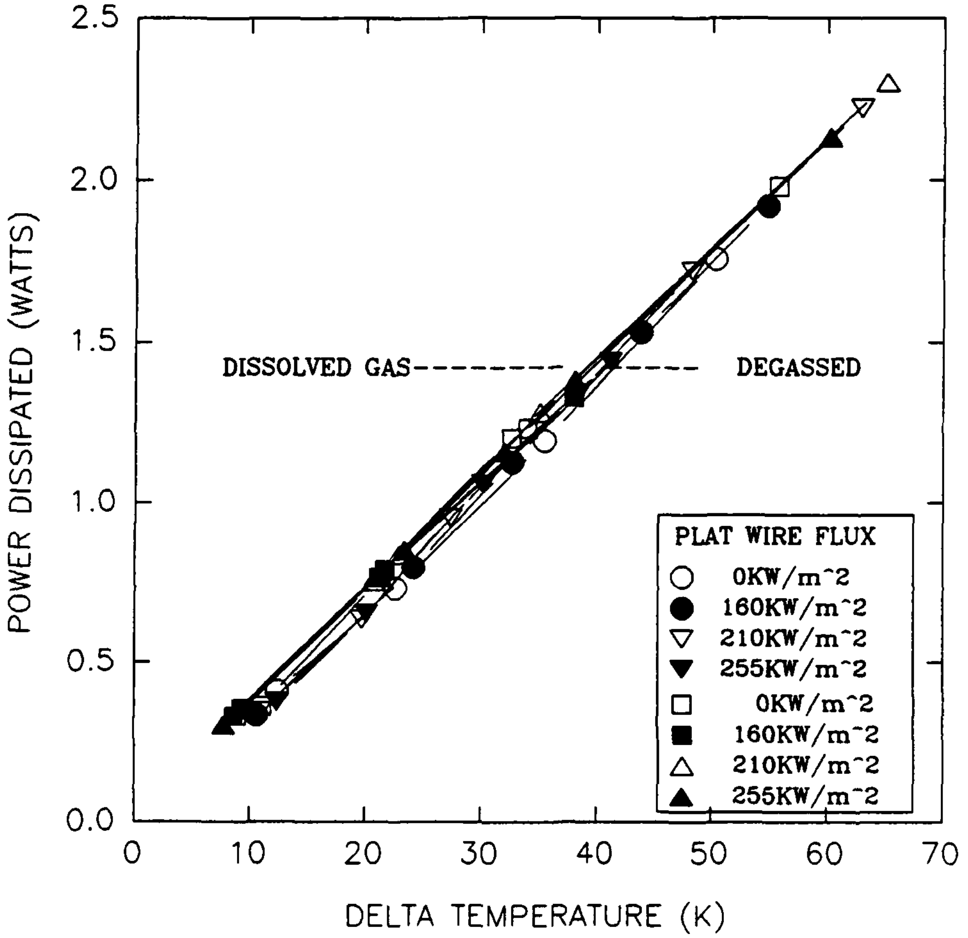

FIGURE 27. CHIP 4, LIDS ON, DEGASSED FLUID VS FLUID WITH DISSOLVED GASSES

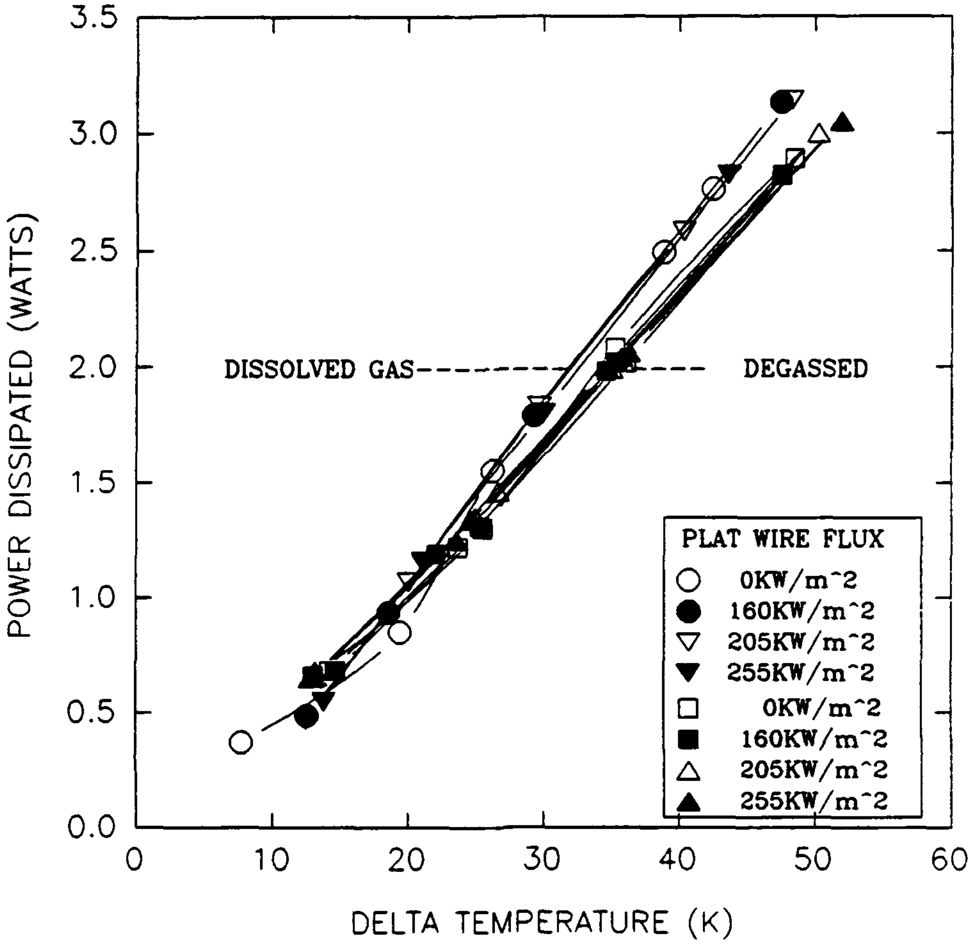

FIGURE 28. CHIP 2, LIDS OFF, DEGASSED FLUID VS FLUID WITH DISSOLVED GASSES

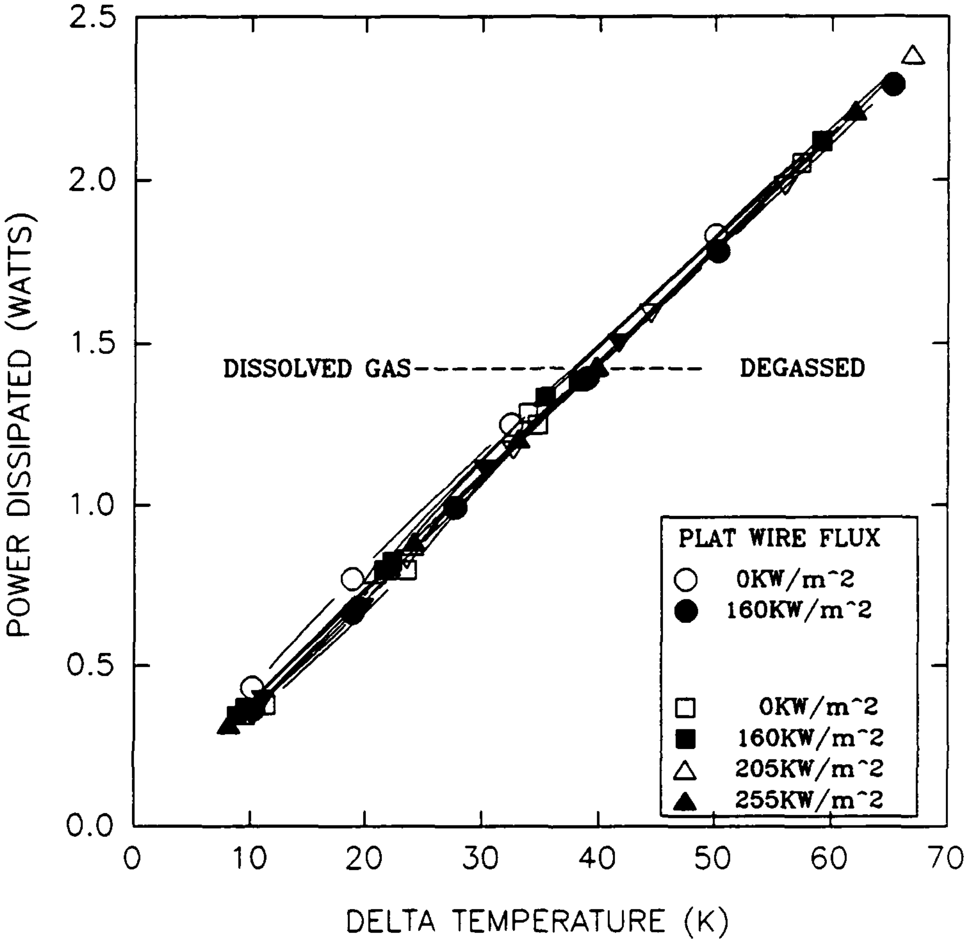

FIGURE 29. CHIP 2, LIDS ON, DEGASSED FLUID VS FLUID WITH DISSOLVED GASSES

V. CONCLUSION

This study investigated the effects of the boiling wake from a platinum wire on the heat transfer from the chips. Experiments were conducted with FC-72 fluid which was degassed and fluid which was not degassed prior to the run.

A. LIDS ON VERSUS LIDS OFF

1. By removing the lids from the chips, the chips were able to maintain a constant temperature and yet dissipate a great deal more power. For example, with 50.0 degrees Celsius of temperature difference between the chip and the fluid, the chips with lids were able to only dissipate 1.8 watts of power. With the lids removed, the chips were able to operate at 68% higher power level, 3.02 watts on average, while maintaining the same 50.0 degrees Celsius of temperature difference. Table 2 contains a summary of this data.

2. This phenomenon was noted for both the degassed fluid and the fluid which contained dissolved gasses, regardless of power setting of the platinum wire.

B. DEGASSED FLUID VERSUS FLUID WITH DISSOLVED GASSES

1. The data for the chips immersed in the degassed fluid

was very similar to the data for the chips immersed in fluid containing dissolved gasses.

2. The chips which were immersed in the fluid containing dissolved gasses were slightly cooler at the same power settings than the chips immersed in the degassed fluid. This phenomenon is a temporary one, which will only last while the fluid contains the dissolved gas. After a few hours of heating, the fluid will be degassed, and this phenomenon will cease. Figures 24-29 contain plots of the degassed fluid and the fluid containing dissolved gasses.

C. INFLUENCE OF PLATINUM WIRE'S HEAT FLUX ON THE CHIP'S TEMPERATURE

1. The plume from the platinum wire failed to enhance the heat transfer from the chips.

2. The degassed data was closely grouped, with little variation. The data was very linear for all fluxes from 0 W/m^2 to 260 KW/m^2. Figures 20-23 contain the plots of the degassed data.

D. HYSTERESIS PHENOMENON

The previous study found that a constant source of bubble generation from below is an effective way to eliminate the boiling curve overshoot and hysteresis loop associated with dielectric fluids (Ref 4 Pg 44). This study found that these two phenomena did not occur either in the chips with or without lids, nor did it occur in the degassed fluid or in the fluid which contained dissolved gases. The platinum wire used in the previous study, was extremely smooth and thus did not contain many nucleation sites. The chip surface was not as smooth and thus contained a great number of nucleation sites. Consequently, the conditions to cause the boiling curve overshoot and the hysteresis loop were not present in this study.

E. DAMAGE TO CHIPS WITHOUT LIDS

The chips were immersed in the fluid with their lids removed for three weeks. The chips, without lids, were operated at various power settings for approximately 50.0 hours. After the experiments were conducted, the chips were examined under an optical microscope. The chip surface appeared undamaged. The hairs which connect the chip to the base were all attached and did not appear to be bent. No sign of discoloration or corrosion was found on any of the five chips which were operated without their lids. The five chips which were operated under these conditions were compared with two chips which had their lids removed after the experiment. For all intents and purposes, all seven chips remained identical. Figures 14-16 are photographs of various chips at various magnifications.

APPENDIX A CALIBRATION

The twelve thermocouples, five chip temperature sensors and the platinum wire were calibrated in a heated bath utilizing a platinum resistance thermometer as a temperature standard.

A. INITIAL CALIBRATION EQUIPMENT

The following equipment was utilized to calibrate the various temperature sensors. The setup was identical to the one utilized by Egger reference 4.

The bath was filled with Ethylene Glycol, was externally heated and the fluid was circulated by a centrifugal pump to ensure a uniform bulk fluid temperature. The temperature of the fluid was measured by utilizing a highly sensitive commuting bridge which measured the resistance of a platinum resistance temperature probe. This probe was previously calibrated to a standard traceable to the National Bureau of Standards.

The calibration system consisted of the following components:

1. Rosemount Engineering Co. Model 913A calibration bath

with Ethylene Glycol as the working fluid.

2. Rosemount Engineering Co. Model 923B power supply, controlling calibration bath temperature.

3. Rosemount Engineering Co. Model 920A commutating bridge, used to measure resistance with 0.001 ohm accuracy.

4. Rosemount Engineering Co. Model 162C S/N 985 Platinum Temperature Probe, used to measure the calibration bath temperature through the commutating bridge.

5. Hewlett Packard Data Acquisition System, used to measure the twelve thermocouple voltages, the voltage of the five chip temperature sensors, and the voltage drop across the platinum wire feed a constant .001 amp current.

B. DATA ACQUISITION EQUIPMENT

The calibration was conducted by measuring the voltages of the twelve thermocouples, and the five chip temperature sensors and platinum wire which was feed a constant .001 amp current. These voltages were measured by the following data acquisition equipment.

1. Hewlett Packard 3456A Digital Voltmeter which measured the voltage.

2. Hewlett Packard 3497A Data Acquisition/Control Unit which contained two cards, an unmodified HP 44422A 20 Channel T-Couple Acquisition Board and a modified HP 44422A 20 Channel T-Couple Acquisition Board. The first was used to measure the twelve thermocouples' voltage. The second card measured the five voltage drops across the chips' temperature sensors and the voltage drop across the platinum wire. The second unit also provided the chips with the constant 0.001 amp current.

3. A second Hewlett Packard 3497A Data Acquisition/Control Unit whose sole function was to provide the first unit with a constant .001 amp current.

C. CALIBRATION PROCEDURE

The following procedure was used with the previously described components for measuring temperature and resistance to obtain the system's calibration data:

1. Carefully insert the components into the liquid bath. Extreme care must be taken to ensure the platinum wire is not broken or deformed.

2. Set the calibration bath controller to 40 C.

3. Allow bath temperature to stabilize.

4. Once the stabilized temperature is reached, allow the components to come to thermal equilibrium with the bath, this takes approximately five minutes.

5. Take temperature measurements with the platinum wire temperature probe, before and after the voltages for the various components are recorded. Record the voltage outputs of the five chip temperature sensors, twelve thermocouples, and the platinum wire.

6. Set the bath temperature for a 20 C temperature increase.

7. Repeat steps 3 thru 6 until 100 C reading is achieved.

8. Activate the systems external cooling system.

9. With temperature control setting decreasing at 20 C intervals, repeat steps 3 thru 6 until 40 C is reached.

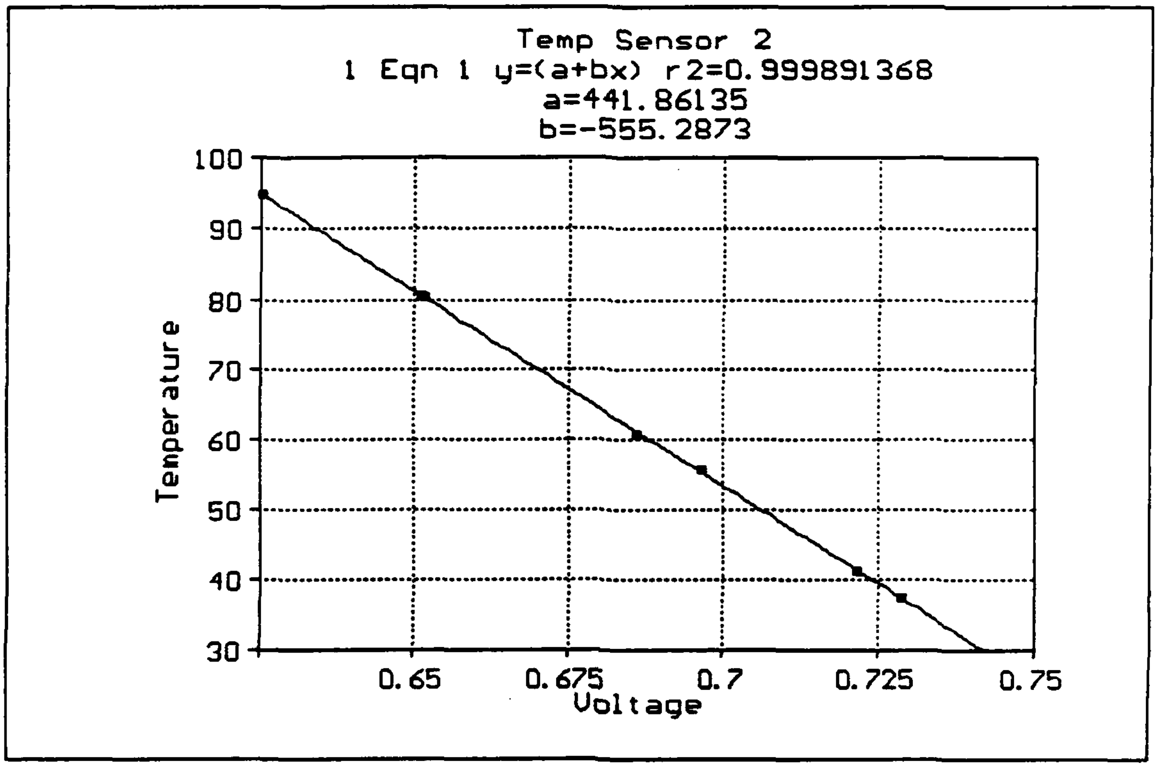

FIGURE 30. CHIP 2 CALIBRATION CURVE

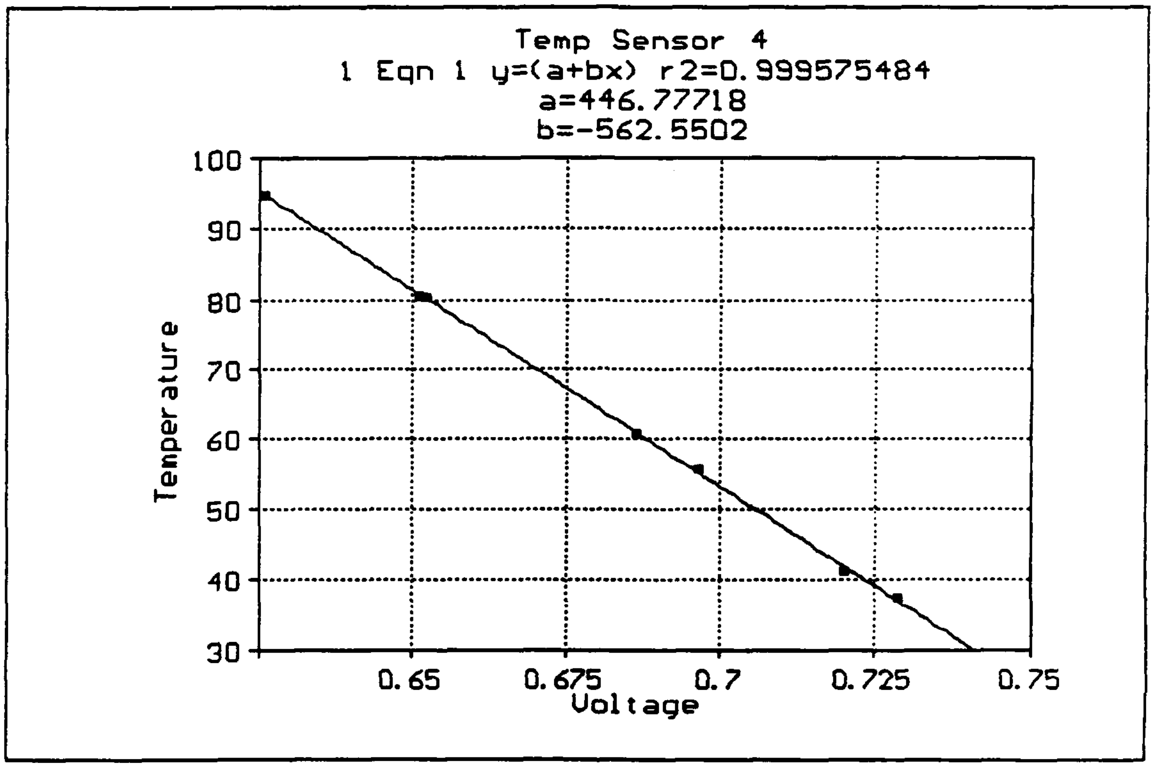

FIGURE 31. CHIP 4 CALIBRATION CURVE

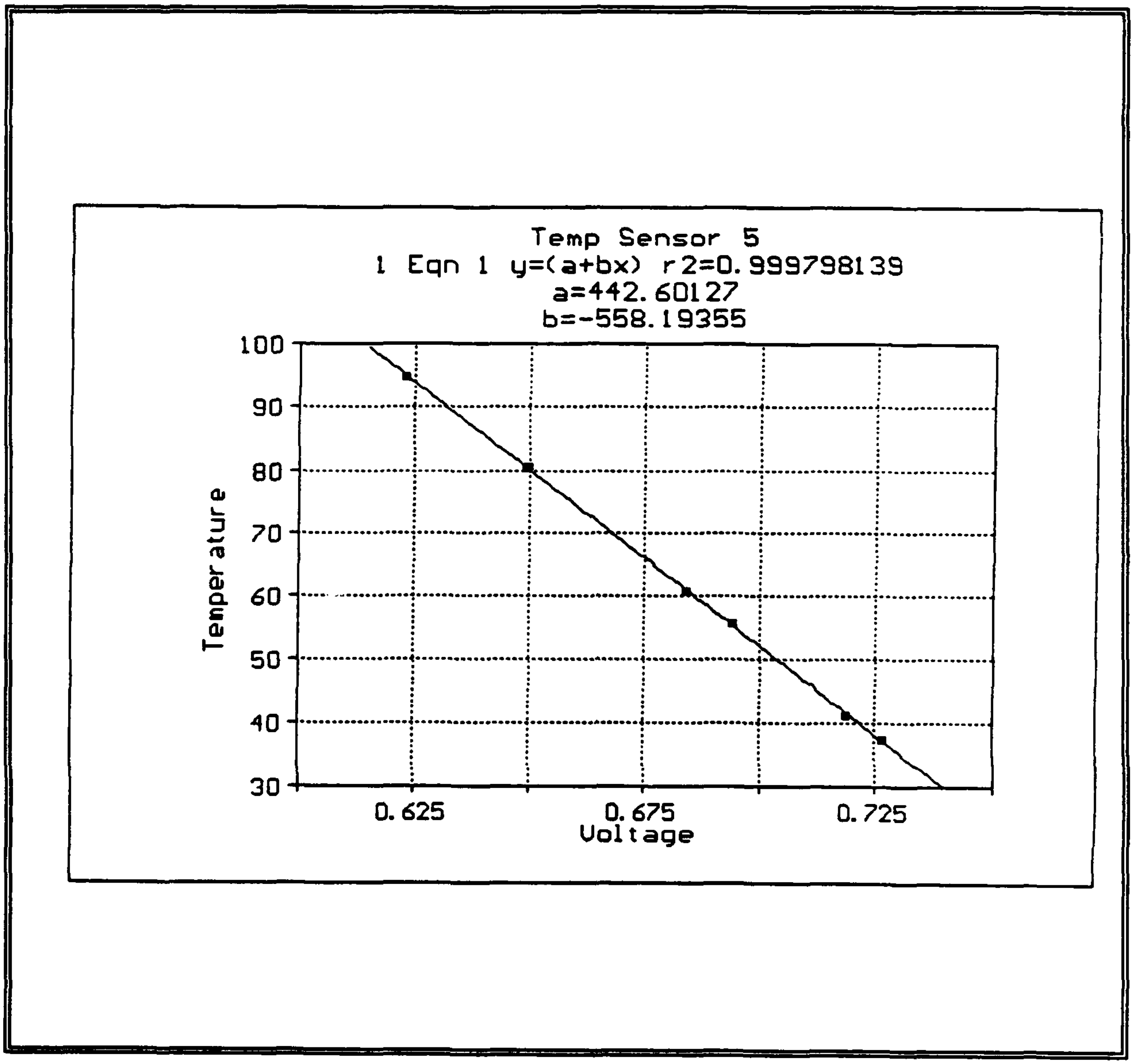

FIGURE 32. CHIP 5 CALIBRATION CURVE

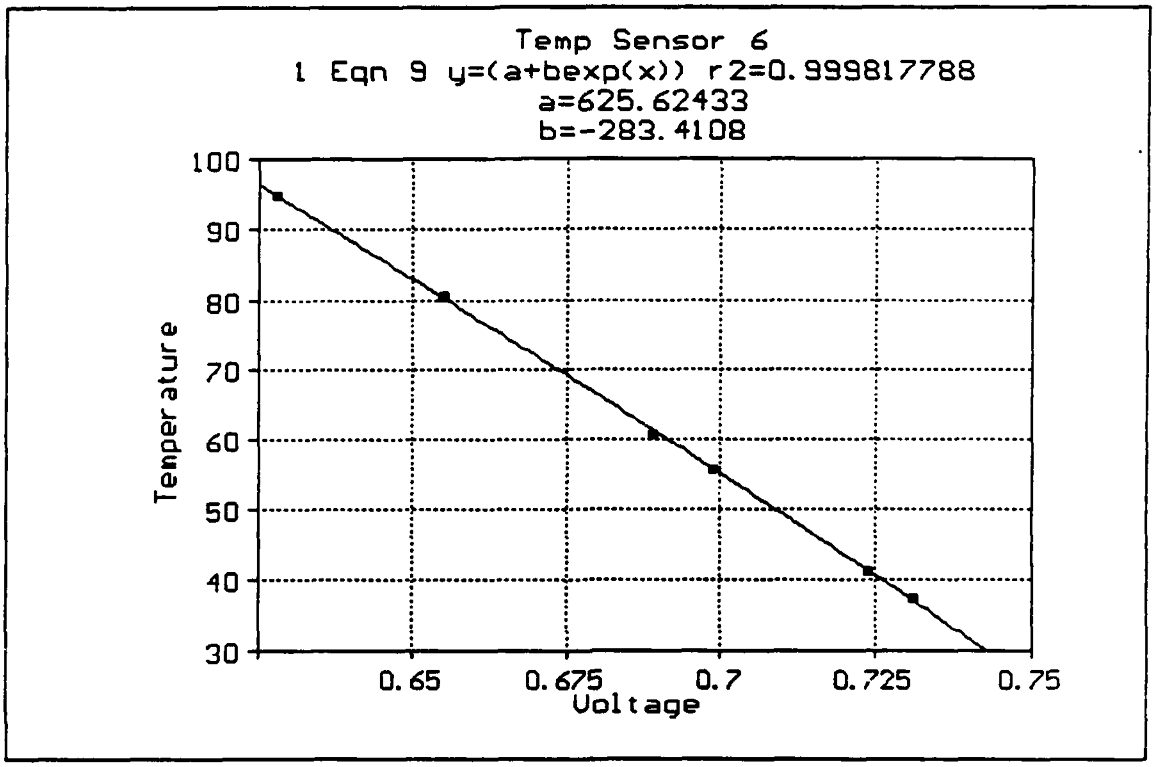

FIGURE 33. CHIP 6 CALIBRATION CURVE

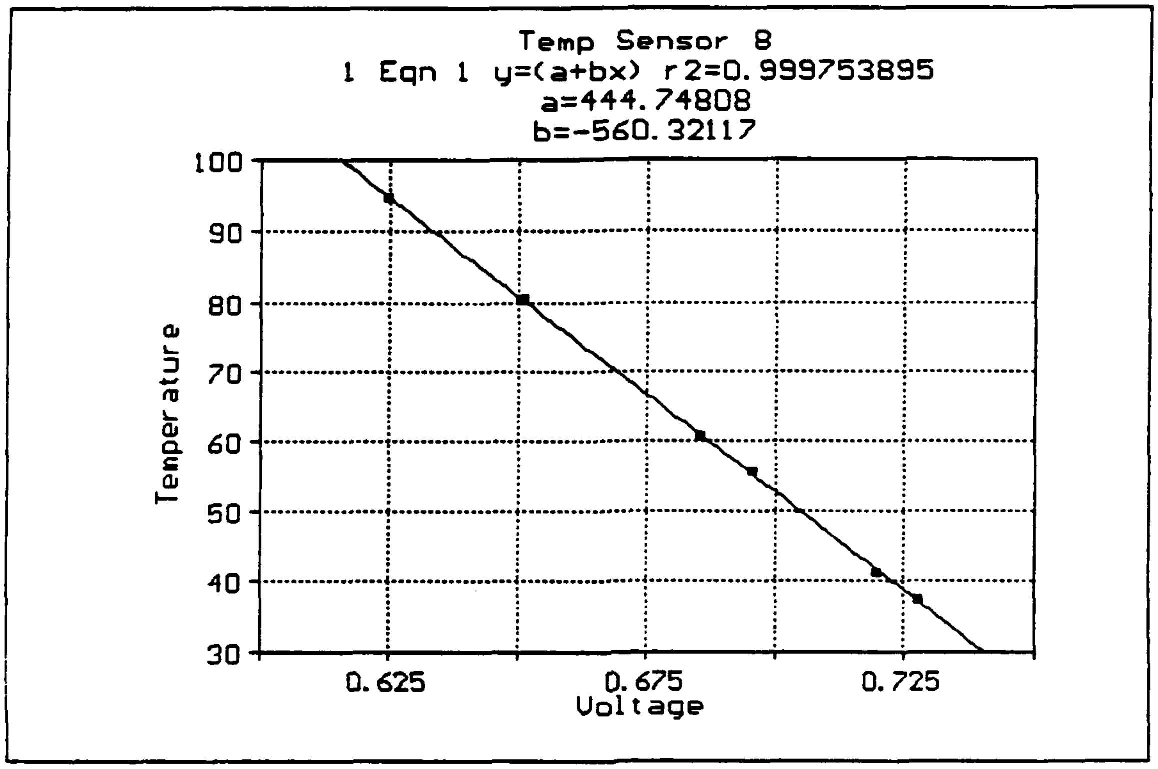

FIGURE 34. CHIP 8 CALIBRATION CURVE

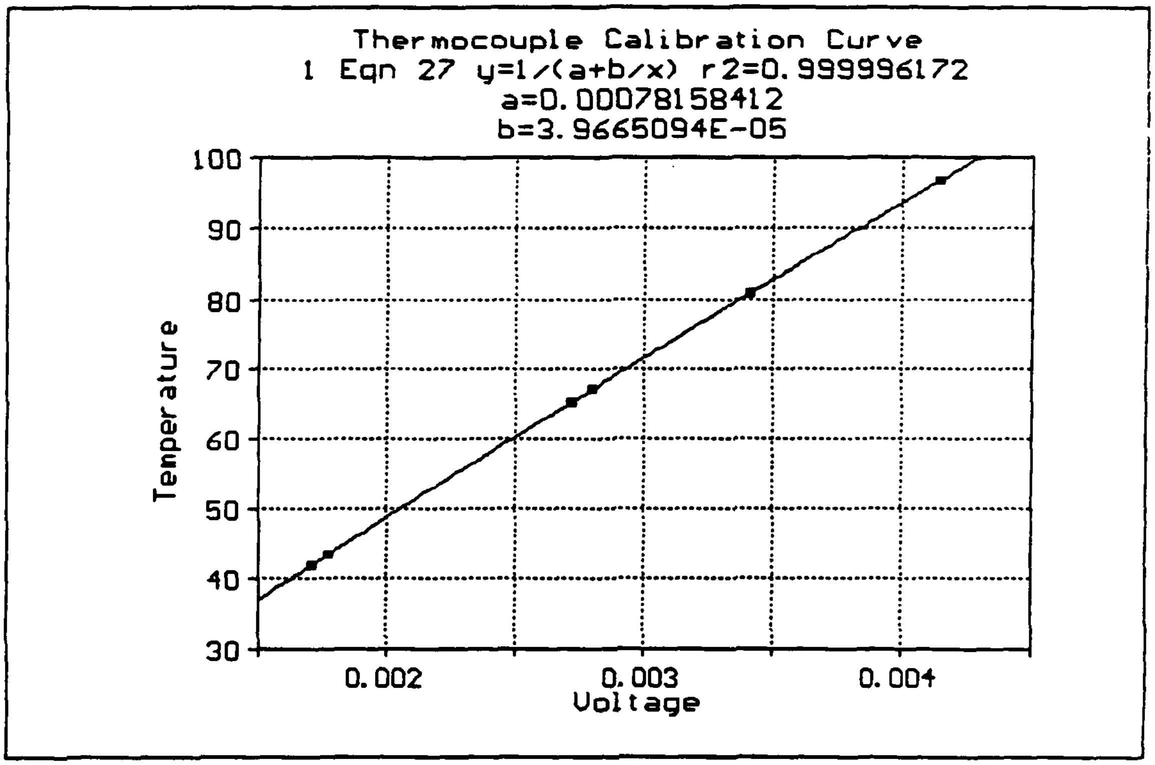

FIGURE 35. THERMOCOUPLE CALIBRATION CURVE

APPENDIX B SAMPLE CALCULATIONS

A. DETERMINATION OF INPUT POWER OF CHIP

For this sample calculation, the power drop across chip 2 was determined:

Power1= Volt1*Volt2/Resist1

where Volt1 and Volt2 are the voltages across the chip and the precision resistor, and Resist1 is the resistance of the precision resistor.

Power1 = 2.0*1.0/2.0076 = 0.996 Watts

B. DETERMINATION OF HEAT FLUX ACROSS CHIP

For this sample calculation, the heat flux across chip 2 was determined:

Flux1= Power1/Area1

Power1 is the power drop across chip 2 and the Area1 is equal to the length times width of the chip face:

Area1 = length * width = 0.00797m *0.00797m

= 6.3*10^-5 m^2

Flux1= 0.996 /0.000063 = 15,809 W/m^2

C. DETERMINATION OF POWER DROP ACROSS THE PLATINUM WIRE

For this sample calculation, the power drop across the platinum wire was determined:

Power2=Volt3*Volt4/Resist2

Volt3 is the voltage drop across the Platinum wire, Volt4 is the voltage drop across the precision resistor, and Resist2 is the resistance of the precision resistor:

Power2= 0.6 Volts * 0.0487 Volts/0.487 Ohms

= 0.06 Watts

D. DETERMINATION OF HEAT FLUX ACROSS THE PLATINUM WIRE

For this sample calculation, heat flux across the platinum wire was determined:

Flux2 = Power2/Area

Power2 is the power drop across the platinum wire and the Area is equal to pi times the length times the diameter of the wire:

Area = 3.14159 * 0.103293 m * 0.00005 m

= 1.622E-5 m^2

Flux2= 0.06 Watts/1.622E-5 m^2 = 39988.9 Watts/m^2

E. THERMOCOUPLE CONVERSION FROM VOLTAGES TO TEMPERATURE

For this sample calculation, the temperature of the thermocouple was determined in the following way:

T(I) = 1.0/(A + B/Volt(I))

A and B are constants equal to 0.0008011067 and 0.00003961586 respectively. These two values were determined during the calibration procedure, Appendix A contains the calibration curves for the chips and thermocouple.

T(I) = 1.0 / (0.0008011067 + 0.00003961586/0.001) = 24.74 Celsius

F. CONVERSION FROM VOLTAGES TO TEMPERATURE FOR THE CHIP 8

For this sample calculation, the temperature of the chip 8 was determined in the following way:

T8= C + D*Voltage5

Where C and D are constants which are equal to 444.748 and -560.321. These two values were determined the calibration procedure, which is listed in Appendix A. Voltage is the voltage drop across the temperature sensor.

T8 = 444.748 - 444.748 * 0.693596 = 56.11 C

G. DETERMINATION OF THE BULK FLUID TEMPERATURE

For this sample calculation, the bulk fluid temperature was found to simply be the average of the four thermocouples suspended in the liquid. The bulk temperature was determined in the following way:

Tbulk = (T1 + T2 + T3 + T4)/4.0

Tbulk = (56.64 + 56.48 + 56.69 + 56.50)/ 4.0 = 56.58 C

APPENDIX C. UNCERTAINTY ANALYSIS

A. UNCERTAINTY ANALYSIS IN SURFACE AREA OF PLATINUM WIRE

$$w_D=0.003mm$$

$$w_L=1.0mm$$

$$A=\Pi DL$$

where:

D = Wire Diameter

L = Wire Length

A = Platinum Wire Surface Area

$$\frac{\delta A}{\delta D}=(\Pi L)$$

$$\frac{\delta A}{\delta L}=(\Pi D)$$

Therefore,

$$w_A=\sqrt{(\Pi l w_d)^2+(\Pi D w_L)^2}$$

$$\frac{w_A}{A}=\sqrt{(\frac{w_D}{D})^2+(\frac{w_l}{L})^2}$$

$$=\sqrt{(\frac{0.003}{0.08})^2+(\frac{1.0}{105.66})^2}$$

$$\frac{w_a}{A}=0.061 \; or \; 6.1\%$$

$$w_A=1.008E\text{-}6m^2$$

B. UNCERTAINTY IN POWER

$w_{V,2\Omega}$ *and* $w_{V,0.487}=$ 0.007% [*Ref*11, *PG* 668]

W_{chip} or $W_{pt,wire}$ = 0.007% [Ref11,pg.668]

$W_{R,2\Omega}$ = $W_{R,0.487}$ = $\pm 0.001\Omega$ max value

$$Q_{ptwire} = V_{ptwire} x I_{ptwire} \quad \text{and} \quad Q_{chip} = V_{chip} x I_{chip}$$

$$I_{ptwire} = \frac{V_{0.487\Omega}}{R_{0.487OMEGA}} \quad \text{and} \quad I_{chip} = \frac{V_{2.0\Omega}}{R_{2.0\Omega}}$$

$$\frac{\delta Q}{\delta V_{ptwire}} = \frac{V_{0.487\Omega}}{R_{0.487}} \quad \text{and} \quad \frac{\delta Q}{\delta V_{chip}} = \frac{V_{2.0\Omega}}{R_{2.0\Omega}}$$

$$\frac{\delta Q}{\delta V_{2.0\Omega}} = \frac{V_{chip}}{R_{2.0OMEGA}} \quad \text{and} \quad \frac{\delta Q}{\delta V_{0.487\Omega}} = \frac{V_{ptwire}}{R_{0.487\Omega}}$$

$$\frac{\delta Q}{\delta R_{0.487\Omega}} = -V_{ptwire} * \frac{V_{0.487\Omega}}{R^2_{0.487\Omega}}$$

$$\frac{\delta Q}{\delta R_{2.0\Omega}} = -V_{chip} * \frac{V_{2.0\Omega}}{R^2_{2.0\Omega}}$$

$$w_{q,ptwire} = \sqrt{(\frac{V_{0.487\Omega}}{R_{0.487\Omega}} * w_{v,ptwire})^2 + (\frac{V_{ptwire}}{R_{0.487\Omega}} * w_{V,0.487\Omega})^2 + (-V_{ptwire} * \frac{V_{0.48}}{R_{0.48}}}$$

$$w_{Q,chip} = \sqrt{(\frac{V_{2.0\Omega}}{R_{2.0\Omega}} * w_{V,chip})^2 + (\frac{V_{chip}}{R_{2.0\Omega}} * w_{V,chip})^2 + (-V_{chip} * \frac{V_{2.0\Omega}}{R_{2.0\Omega}} * w_{2.0\Omega})^2}$$

$$\frac{w_{Q,ptwire}}{Q} = \sqrt{(\frac{w_{v,ptwire}}{V_{ptwire}})^2 + (\frac{w_{V,0.487\Omega}}{V_{0.487\Omega}})^2 + (\frac{w_{0.487\Omega}}{R_{0.487\Omega}})^2}$$

$$\frac{w_{Q,chip}}{Q} = \sqrt{(\frac{w_{V,chip}}{V_{chip}})^2 + (\frac{w_{V,2.0\Omega}}{V_{2.0\Omega}})^2 + (\frac{w_{2.0\Omega}}{R_{2.0\Omega}})^2}$$

The worst case for the platinum wire will occur when the wire is set at the lowest heat flux setting 160KW/m^2. At this point the voltage drop across the 0.487 Ohm resistor is 0.31 Volts and the voltage drop across the platinum wire is 4.313 Volts.

$$w_{Q,ptwire} = \sqrt{(0.007\%)^2 + (0.205\%)^2 + (2.04E\text{-}5\%)^2}$$

$$= 2.05\ \text{E-3 or } 0.205\%$$

The lowest power setting the chips were operated at was 0.34 Watts. At this output setting the voltage drop across the chip was 7.823 Volts and the voltage drop across the 2.0 Ohm resistor was 0.0868 Volts.

$$\frac{w_{Q,chip}}{Q} = \sqrt{(0.007\%)^2+(0.05\%)^2+(0.000005\%)^2}$$

$$= 5.05\text{ E-4 or } 0.0505\%$$

C. UNCERTAINTY IN HEAT FLUX

$$q=\frac{Q}{A}$$

$$\frac{\delta q}{\delta Q} = \frac{1}{A}$$

$$\frac{\delta q}{\delta A} = -\frac{Q}{A^2}$$

$$w_q = \sqrt{(-\frac{Q}{A^2}w_A)^2+(\frac{1}{A}w_A)^2}$$

$$\frac{W_q}{Q} = \sqrt{\left(\frac{W_A}{A}\right)^2+\left(\frac{W_q}{Q}\right)^2}$$

$$= \sqrt{(0.061)^2+(1.36E-4)^2}$$

= 6.1 E-2 or 6.1%

D. UNCERTAINTY IN CHIP TEMPERATURE AND THERMOCOUPLE TEMPERATURE

The chip's temperature sensors and the thermocouples uncertainty were determined by the uncertainty in the platinum wire temperature probe and the error in matching the temperature sensor and thermocouple to the temperature of the probe.

$$W_{chip} = \sqrt{(W_{ptprobe})^2+(W_{chip})^2}$$

= 0.2502 Celsius

$$W_{TC} = \sqrt{(W^2_{ptprob}+(W_{TC})^2}$$

= 0.037 Celsius

APPENDIX D SOFTWARE

The following computer program was written in Basic 4.0 to control.the HP3497A, record numerous voltages and calculate processed data. The program first recorded the output data from the data acquisition system. This data included voltage drops across the chips, the voltage drop across the chips' temperature sensors, the voltage drop across the precision resistors and the platinum wire, and the thermocouples voltage. This data was next processed to compute the temperature of the five chip temperature sensors and the twelve thermocouples. It also computed the power drops and the heat flux across the components and the platinum wire

```
10    !FILE ACQUIRE15
20    !
30    !WRITTEN BY FRANK A. ARATA, LT, USN
40    !
50    !THIS PROGRAM CONTROLS THE HP3497 DATA ACQUASITION UNIT
60    !OBTAINS DATA, PROCESSES IT AND OUTPUTS THE THERMOCOUPLE TEMPERATURES
70    ! AND VOLTAGES, THE BULK FLUID TEMPERATURE, THE CHIPS TEMPERATURE, VOLTAGE
80    ! DROP, AND THE CHIP'S AND PLATINUM WIRE POWER DROP AND HEAT FLUX.
90    !ASSIGN OUTPUT TO AN INK JET PRINTER
100   DIM Emf(0:75),T(0:75)
110   PRINTER IS 701
120   BEEP
130   PRINT "DATA TAKEN BY ARATA"
140   !
150   PRINT "THE FLOURINERT USED WAS : FC72"
160   !
170   INPUT "ENTER THE TIME AND THE DATE",A$
180   PRINT "THE TIME AND DATE IS:",A$
190   INPUT "THE PURPOSE OF THE RUN",A$
200   PRINT "THE PURPOSE OF THIS RUN IS:",A$
210   !
220   !AR RESETS THE DATA AQUISITION SYSTEM.AF IS THE FIRST CHANNEL, AL IS LAST
       CHANNEL.
230   OUTPUT 709;"AR AFOO AL11"
240   !F1 SETS THE FUNCTION TO DC VOLTS. R1 SETS THE RANGE TO AUTO.
250   !T1 SETS TRIGGER TO INTERNAL. Z0 SETS AUTO ZERO TO OFF.
260   !FLO SETS FILTER TO OFF.
270   OUTPUT 722;"F1 R1 T1 Z0 FLO"
280   PRINT
290   PRINT
300   PRINT "CHANNEL   THERMOCOUPLE TEMPERATURE"
310   !
320   FOR I=0 TO 11
330   !AS CAUSES THE DAS TO ANALOG STEP THROUGH THE CHANNELS.
340   OUTPUT 709;"AS"
350   WAIT 1
360   !ENTER SENDS VOLTAGES FROM DVM TO DAS.
370   ENTER 722;Emf(I)
380   A=.0000011067
390   B=.03961586
400   Emf(I)=Emf(I)*1000
410   T(I)=1/(A+B/Emf(I))
420   !OUTPUTS THE THERMOCOUPLES TEMPERATURE AND VOLTAGE
430   PRINT I,T(I)
440   PRINT
450   BEEP
460   NEXT I
470   ! AF RESETS DAS
480   T(12)=(T(0)+T(1)+T(2)+T(4))/4
490   !T(12) IS THE AVERAGE TEMPERATURE OF THE FC72 FLUID
```

```
500  PRINT 12,T(12)
510  PRINT
520  OUTPUT 709;"AR AF54 AL59"
530  FOR I=54 TO 59
540  OUTPUT 709;"AS"
550  WAIT 1
560  ENTER 722;Emf(I)
570  BEEP
580  NEXT I
590  !T(55)-T(59) ARE THE EQN OBTAINED FOR THE TEMPERATURE SENSORS TO THE CHIPS
600  !WHICH WERE OBTAINED DURING CALIBRATION. THEY OBTAIN TEMPERATURE FROM  THE
610  !EMF OF THE TEMPERATURE SENSOR.
620  T(55)=444.74808-560.32117*Emf(55)
630  T(56)=625.62433-283.4108*EXP(Emf(56))
640  T(57)=442.60127-558.19355*Emf(57)
650  T(58)=446.77718-562.5502*Emf(58)
660  T(59)=441.86135-555.2873*Emf(59)
670  PRINT
680  PRINT
690  PRINT "THE CHIPS TEMPERATURE, COMPONENTS 8,6,5,4,2"
700  PRINT
710  PRINT
720  PRINT "THERMO              TEMP                    DELTA T                 EMF"
730  PRINT
740  FOR I=55 TO 59
750  PRINT I,T(I),T(I)-T(12),Emf(I)
760  NEXT I
770  !
780  !
790  !NEXT POWER DROP AND HEAT FLUX ACCROSS THE FIVE CHIPS AND THE PLAT. WIRE
800  !
810  OUTPUT 709;"AR AF60 AL70"
820  FOR I=60 TO 70
830  OUTPUT 709;"AS"
840  WAIT 1
850  ENTER 722;Emf(I)
860  BEEP
870  NEXT I
880  !
890  Power(1)=Emf(60)*Emf(65)/(3*1.9994)
900  Power(2)=Emf(61)*Emf(66)/2.0076
910  Power(3)=Emf(62)*Emf(67)/1.9998
920  Power(4)=Emf(63)*Emf(68)/2.0018
930  Power(5)=Emf(64)*Emf(69)/(3*2.0025)
940  Power(6)=Emf(54)*Emf(70)/.4892
950  Heat_flux=Power(6)/.00001653
960  Current=Emf(70)/.4892
970  Resit=Emf(54)/Current
980  PRINT
990  PRINT
1000 PRINT "THE RESISTANCE OF THE PLATINUM WIRE IS :",Resit
1010 PRINT
1020 PRINT "THE TEMPERATURE OF THE PLATINUM WIRE IS:",Temp_wire
1030 PRINT
1040 PRINT
1050 PRINT "THE POWER DROP OVER CHIP 2 IS:",Power(2)
1060 PRINT "THE FLUX ACROSS CHIP 2 IS IN W/m^2:",Power(2)/.000063
1070 PRINT "THE POWER DROP OVER CHIP 4 IS:",Power(1)
1080 PRINT "THE FLUX ACROSS CHIP 4 IS IN W/m^2:",Power(1)/.000063
1090 PRINT "THE POWER DROP OVER CHIP 5 IS:",Power(3)
1100 PRINT "THE FLUX ACROSS CHIP 5 IS IN W/m^2:",Power(3)/.000063
1110 PRINT "THE POWER DROP OVER CHIP 6 IS:",Power(5)
1120 PRINT "THE FLUX ACROSS CHIP 6 IS IN W/m^2:",Power(5)/.000063
1130 PRINT "THE POWER DROP OVER CHIP 8 IS:",Power(4)
1140 PRINT "THE FLUX ACROSS CHIP 8 IS IN W/m^2:",Power(4)/.000063
1150 PRINT "THE POWER DROP OVER THE PLATINUM WIRE IS:",Power(6)
1160 PRINT
1170 PRINT "THE HEAT FLUX ACROSS THE PLATINUM WIRE IN w/m^2 IS:",Heat_flux
1180 PRINT
1190 PRINT
1200 PRINT
1210 END
```

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